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THE MINOR PLANETS

by F. Yu. Zigel'

"Nauka" Press, Moscow, 1969

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Where did that group of minor planets come from, revolving around the Sun between the orbits of Mars and Jupiter? Are the minor planets related to the meteorites that strike the Earth? What role could the minor planets play in the plans for the conquest of space? These are a few of the questions discussed in this book by F. Yu. Zigel.

The reader will also learn about the history of the study of asteroids, modern methods of investigating them, and about some of the interesting minor planets—Icarus, Hermes, Eros and others.

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F. Yu. Zigel'

"The main purpose and first steps refer to man's entrance into the ether, using solar energy and, masses scattered everywhere, such as asteroids and even smaller bodies." .....K. E. Tsiolkovskiy, *"Tseli Zvezdoplavaniya,"* [The Purposes of Space Flight].

ASTEROIDS - THEIR SIGNIFICANCE TODAY

In the structure of the solar system there is a peculiarity which evidently /3* is not at all characteristic of all planetary systems. This is the belt of small** planets whose orbits, with rare exceptions, are located between those of Mars and Jupiter. Even the largest of these bodies appear in an average sized telescope as star-shaped, as objects moving across the background of constellations. This is the origin of the other designation of small planets--asteroids, in the literal translation from Greek meaning "similar to stars".

The opinion has been expressed that the asteroid zone represents a secondary, inessential detail of the Solar System. In textbooks on astronomy--whether school or university--the small planets are given short shrift. There are very few books devoted especially to this subject and up to the present time the detailed monograph of I. I. Putilin [1] has been unique in the astronomical literature of the world. In spite of the many years' work and extremely fruitful activity of some observatories and institutes specializing in this field, the study of the small planets is still conducted mainly from the position of celestial mechanics. Astrophysical investigations of the asteroids are isolated and are not guided by any one purposeful program.

This state of affairs was partially promoted by a temporary slackening of interest in the study of the planets in general which occurred during the first

*Numbers in the margin indicate pagination in the foreign text.
**[Note: The translator has used the term "small" rather than "minor" throughout.]

half of the present century. The wonderful achievements of stellar astronomy temporarily displaced planetary astronomy to a secondary level. Research on planets has become the almost exclusive property of amateur astronomers.

As D. Kuiper [2] justly states, "Professional astronomers with their large telescopes have been so busy with the surprising problems of the stars, nebulae, star clusters, galaxies and the stellar universe that astronomy almost became the exclusive study of the stars." It was natural that this unfavorable situation had particular reference to the study of the small planets. /4

The coming of the space age led to a reevaluation of values in all areas of human activity including astronomy. It seemed that astronomy, destined forever to be a purely "observational" study, suddenly turned into an experimental science right before our eyes.

Near space is becoming the arena of practical human activity. Plans for the near future to tread upon the surface of the Moon and then on the nearer planets appear quite reasonable today. Under these conditions it is completely normal for planetary astronomy to have a rebirth. It is becoming a very important aid in astronautics.

From the point of view of astronautics, asteroids are chiefly interesting from two aspects. During future voyages of space equipment through the planetary zone (Figure 1), danger from meteors will substantially increase. A quantitative evaluation of this danger for concrete trajectories of spacecraft can obviously be made with confidence only when the structure and composition of the asteroid ring are sufficiently well-known by us. The relatively tiny mass of the asteroids, theoretically speaking, will facilitate landing on and departing from the largest of these small planets. On the other hand, however, such a landing in connection with a lack of atmosphere around the asteroids will not be able to make use of the "atmospheric brake." In current astronautical literature are even found assignments which look fantastic at first glance, such as the exploitation of raw materials from the asteroids and the transportation of some of them, the most valuable, to a portion of the Earth's orbit for processing, so to say, "on the spot."

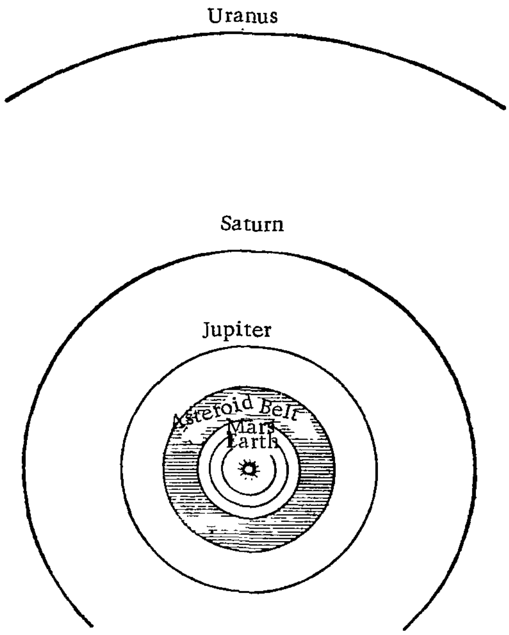

Figure 1. The Asteroid Belt.

It is possible to evaluate the actuality and technical feasibility of these partial tasks within the general plan of conquering near space in different ways. It is beyond doubt, however, that the significance of the /5 asteroids for contemporary science is far from having played its full role in the future astronautic activity of mankind. Even today the study of the asteroids carried on directly from different points of view can lead to the solution of some important scientific problems.

The small planets are still individual celestial bodies which we study in two ways, by astronomical methods and, in contrast, directly in earth laboratories. The fact is that, in those cases where the orbits of meteorites can be determined with sufficient accuracy, it is clear that they approach the earth from the very heart of the asteroid belt. In other words, there is no doubt of the fact that the overwhelming number of meteorites (if not all) and small planets are bodies of one nature and of one origin. In those cases where the orbit of an asteroid is greatly drawn /6 out (which is characteristic of only the smallest ones) and intersects the orbit of the Earth, the possibility arises of a direct collision of the asteroid with our planet. In this case the small planet has a chance of ending up in an earthly laboratory.

Research on asteroids is considerably enhanced by the uniform nature of meteorites and asteroids. Combining astronomical data about the small planets with results obained from meteorites can elucidate a number of cosmogonic problems, first and foremost being the cardinal question of the origin of the small planets.

Whether there was ever in the position of the asteroid belt a large planet which catastrophically exploded into a great number of fragments, or whether there have always existed, from the very beginning of the formation of the planetary system, only small bodies which have been gradually breaking up in this region has still not been decisively determined. In the meantime, one solution to this question or another would serve as a "touchstone" for a series of cosmogonic hypotheses.

On the other hand, discoveries in the meteorites of high molecular organic compounds and so-called "organized elements," which many researchers consider remains of extraterrestrial organisms, place before modern science such problems as the evolution of organic substances in space, the origin of life on Earth and its limits. It is possible that the solution to these exciting problems will be found precisely in a joint study of meteorites and asteroids.

Naturally, new problems do not exclude traditional questions solved by means of the asteroids. In the future the movement of the small planets may be involved in complicated problems of celestial mechanics. Just as previously, small planets will be of some use in constructing stellar catalogs.

Nevertheless, these traditional subjects do not determine the future study of the asteroids. Foremost will be problems of astrophysics, cosmogony and astronautics. The complex study of meteorites and asteroids will dominate in current investigations of the small planets.

Asteroids are in the order of the day for current science. We hope that the topicality of the subject will prompt the reader to further and more detailed acquaintance with the small planets.

SOME HISTORY /7

The first discoveries of the small planets were not purely by chance. As early as 1596, in his book *The Mysteries of Cosmography*, Johann Kepler expressed the conjecture that some unknown planet must exist between the orbits of Mars and Jupiter. This enormous region of cosmic space, it seemed, had to be filled with something.

Furthermore, Kepler persistently looked for a connection between the distances of the planets from the Sun and their periods of revolution. By themselves the known planets were not a sufficient base for the construction of a simple, empirical law. Therefore, as Kepler himself writes, "I permitted myself a strange and audacious assumption: I assumed that in addition to the visible planets two other planets exist, invisible because of their extreme smallness, and found between Mercury and Venus and between Mars and Jupiter."

The speculative assumptions of Kepler were confirmed two years later (only partially, it is true) by a remarkable empirical comparison combining the mean distances of the planets from the Sun. In 1772 Johann Titius, professor of Astronomy at Wittenberg, called attention to the fact that the magnitudes of the semi-major axes of the planetary orbits in astronomical units can be respresented quite closely by the formula

$$a_n = 0.4 + 0.3 \cdot 2^n .$$

This table compares the magnitudes a_n, computed by this equation, with the real distances of the planets from the Sun:

Planet	n	Computed distance a_n, AU.	Actual distance, AU.
Mercury	$-\infty$	0.4	0.4
Venus	0	0.7	0.7
Earth	1	1.0	1.0
Mars	2	1.6	1.5
?	3	2.8	--
Jupiter	4	5.2	5.2
Saturn	5	10.0	9.5
Uranus	6	19.6	19.1
Neptune	7	38.8	30.1
Pluto	8	77.2	39.5

[1]An astronomical unit equals the length of the major semi-axis of the Earth's orbit (149.5 million km). It is designated by AU.

In consideration of the fact that at this time the three last planets had not /8 yet been discovered, the coincidence of the regularity observed with reality seemed simply amazing to Titius' contemporaries.

Titius' discovery interested the Berlin astronomer Johann Bode who did not hesitate to give it wide publicity. The "Titius-Bode Law," as the discovered regularity came to be called, received unexpected confirmation very quickly.

On 13 March 1781, William Herschel discovered Uranus. The distance of this new planet from the Sun proved to be very close to that predicted by the Titius-Bode Law. Now, there were few astronomers who doubted that this empirical law reflects an objective relationship of nature. But it followed that between Mars and Jupiter there must also exist a planet with a semi-major axis of the orbit approaching 2.8 AU.

Eight years after the discovery of Uranus, F. Zach tried to compute the orbit of the hypothetical planet and in 1796, at the Astronomical Congress in Goth, a group of 24 astronomers were gathered under the witty designation of "The Celestial Police Detachment." In addition to Zach, there were present such eminent astronomers as Lalande and Schroeter in particular. The task consisted of organizing a systematic search for the undetected planet. For this purpose the entire Zodiacal circle was divided into 24 parts, corresponding to the number of observers.

The search was begun, but the first four years did not lead to the desired result. The discovery was made by Giuseppe Piazzi, Director of the Observatory at Palermo (Sicily), without any connection at all with the "Celestial Police Detachment."

During the night, from the first to second of January 1801, Piazzi was observing the position of the stars in the constellation Thales. This was the next step in a difficult work lasting many years, the compilation of a new stellar catalog. On the following night, Piazzi noted that one of the stars, observed by him the day before, had moved a little to the west, while the other 50 stars had remained fixed. On the third night Piazzi was finally convinced that the moving object was not a star, but a body belonging to the solar system.

Thinking he had by chance discovered a new comet, Piazzi continued his observations, but did not inform anybody in the beginning of the discovery made /9 by him. Only on 24 January did he send a report to Berlin and Milan. Postal service was bad, the times were turbulent because Europe was experiencing the Napoleonic Wars, and Piazzi's letter only reached Berlin on 20 March and Milan even later, 5 April.

It is interesting that during these same months, while Piazzi's letters were heading for their destinations, a young philosopher from Jena, George Hegel, published his dissertation in which he tried to show from a purely speculative position that there could not be more than seven planets in the solar system.

Bode was in Berlin and received Piazzi's letter, but did not know about Hegel's keen polemical and philosophical speculations. He did not know about moment that finally the long sought planet had been discovered. Unfortunately, it was hidden in the Sun's rays at this time and in order to find it again he would have to compute its orbit quite exactly according to Piazzi's observations.

The job was very difficult. Piazzi had observed the planet, discovered and then lost again, for 40 days. During this time it described an arc of about three degrees in the firmament, and the diameter of the Moon only covers about six degrees. In the opinion of the contemporary theoretical astronomers, these data were clearly insufficient for an exact determination of the planet's orbit. A disappointing situation was taking shape and required some kind of solution.

It was found by Karl Gauss, who was at that time a relatively unknown 24--year old reader at the University of Goettingen. Gauss worked out an elegant new aid making it possible to determine the orbit of a celestial body with only three observations of it. Was it possible to find a better way of verifying the new theory?

Equipped with the method of least squares, invented by him even earlier, Gauss applied himself to the computation and by November 1801 he had published his findings. The semi-major axis of the new planet was found to be equal to 2.8 AU, in full agreement with the Titius-Bode Law. Gauss also determined the position of the planet in the sky, but continuously overcast weather hindered the astronomers in again finding the lost planet. Only on December 31, 1801 did Friedrich Olbers, a Berlin astronomer, sight a suspicious starlet, not mentioned on the charts, in the constellation of Virgo, very close to the spot determined by Gauss. Such was the second finding of the planet which received the name of Ceres, the tutelary diety of Sicily, on Piazzi's suggestion. /10

This seemed to be the place to stop. The missing planet had been found, right where it had been expected. Thanks to Gauss, celestial mechanics had enjoyed its next triumph, the Titius-Bode principle received the status of law----"the Law of Planetary Distances." What else of importance could be wished for?

Observing Ceres on 28 March 1802, Olbers observed another unknown starlet, completely unexpected, near it. Two hours' observation convinced him that this object obviously moved against the background of the regular stars. In this way, contrary to expectations, still one more member was added to the list of planets of the Solar System, the small planet Pallas.

In contrast to Ceres, Pallas had an orbit strongly inclined (at an angle of 34°) to the plane of the Earth's orbit and, although its major semi-axis was also found equal to 2.8 AU, the simple diagram of the structure of the solar system seemed to have vanished, hopelessly, for Olbers and his contemporaries.

"Where is that splendid regular order to which the planets were apparently subject in their differences?" wrote Olbers to Bode. "It seems to me that it is still too early to philosophize in this regard; we must first observe and describe the orbits in order to have reliable bases for our assumptions, and maybe then we can determine or at least approximately explain whether Ceres and Pallas have always traveled their orbits in peaceful proximity, but separately from one another, or whether both are only fragments, only pieces of an earlier large planet which some kind of catastrophe destroyed."

Olbers' hypothesis, positioning new ideas of the structure of the solar system, found quick experimental confirmation on those first days, in the opinion of the time. If indeed there had once existed between Mars and Jupiter a large planet which later disintegrated, according to the laws of celestial mechanics its fragments should follow orbits in planes which have a common line of intersection. From this Olbers came to the conclusion that not only Ceres and Pallas, but also all the other still undiscovered small planets (each in its own period) should pass near two points of the sky, one of which is found in the constellation of Virgo, and the other in the constellation of Cetus.

Olbers' prediction was fulfilled in the best way possible; on 2 September /11
1804, Harding found a third asteroid, Juno, in the constellation of Cetus and on 29 March 1807, Olbers himself discovered the fourth asteroid, Vesta, in the constellation of Virgo (Figure 2).

All astronomers were already convinced now that in the space between the orbits of Mars and Jupiter there was evidently a large number of small bodies orbiting around the Sun, the fragments of some catastrophically destroyed planet.

The craving for new discoveries did not only include professional astronomers, but also numerous amateur astronomers. In the name of selfless service to science these enthusiasts converted the garrets of their own residences into domestic observatories. On modest resources, sometimes in a very intricate way, they acquired telescopes and, searchers for new asteroids, spent long nights month after month and year after year in search of a fifth planet. Their diligence was simply amazing, as was the persistence with which they sometimes overcame exceedingly great difficulties, most of all the lack of detailed charts of the zodiacal constellations.

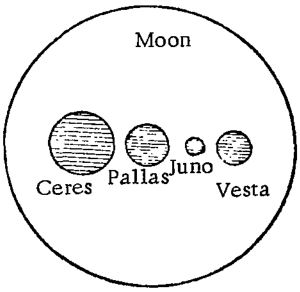

Figure 2. The Size of the Largest Asteroids in Comparison with the Moon.

This is how a close friend of Karl Hencke, a postal official, describes his homemade observatory:

"We went up a high ladder to the clean spacious garret of the hut. I saw only a table and chair--there was no mention of any tower. On the south side of the roof Hencke had removed five tiles, a beam was exposed and formed a suitable aperture. To the beam was attached a wooden frame which the observer could turn in any direction. The telescope was attached to the frame with simple twine."

Another discoverer of small planets was the artist Hermann Goldschmidt who saw a portrait of Galileo in Florence and made two copies of it. One of these he presented to Arago, the famous French astronomer, and the other he traded for a small telescope.

In spite of all his efforts and careful searching, it was only after 15 /12
ceaseless years of seeking, in 1845, that Hencke finally discovered the fifth asteroid, Astraea. Olbers notwithstanding, the orbit of Astraea did not intersect with the orbits of the first four small planets, and this fact aroused the first doubts about the hypothesis of the origin of the asteroid belt in the disintegration of one planet similar to Earth.

At this time, there began a series of discoveries of more and more dwarf planets. After 10 years the catalog of asteroids already included 36 items, and by 1890, 302 small planets had been discovered.

Just as in everything, champions were to be distinguished here: Palisa discovered 83 asteroids, Charlois--72, Wolf--22. It happened that in a single night an observer would succeed in discovering two unknown asteroids at once. For example, this happened twice to Peters and three times to Palisa. In the end, the constantly growing number of discoveries caused some difficulty.

Following longstanding tradition, the first asteroids were given the names of ancient Roman goddesses. However, the "mythological resources" were quickly exhausted and the 45th asteroid was already given the common feminine name "Eugenia." Arbitrariness necessarily replaced tradition. Looking at the current catalog of asteroids, we find names which give testimony to the great resourcefulness of their authors. Is it not amusing that in the solar system there are planets named Industria, Philosophia, Geometria, Photographia, Justitia? Of course geographic names are also used: Russia, Asia, Europa, Australia and many others.

Some asteroids are given women's names, and it is possible to allege that many of the feminine readers of this book will find their names in the catalog of asteroids. Among these planets are Anna, Maria, Elizabetha, Helena, Natalia, Irena and others (but the asteroids Zoya, Zinaida, Nadezhda, Polina...are missing). It is true that a few, including some very important asteroids, have masculine names, e.g., the asteroids Eros, Hermes, Icarus. But even here, as a rule, masculine names acquire feminine endings. This is how the names of asteroids, to which distorted family names of famous Russian scientists have been applied, look: Bredihina, Morozoviya, Belopol'skiya, Tseraskiya, Shternberga...However, in the list of asteroids, it is, e.g., possible to meet with an asteroid as unremarkable as Vitya. The fantasy of the first discoverers of /13
small planets will not be quickly exhausted, and there are still many strange. pretentious names which will appear in future asteroid catalogs. However, even now the application of names sometimes falls behind the rate of new discoveries and about 50 asteroids mentioned in the lists still have only an ordinal number.

At the present time every newly discovered small planet receives a preliminary designation at first.

Along with the year of discovery, there stands a letter of the Latin alphabet, depending on the half of the month in which the planet was discovered. Thus, e.g., if an asteroid is discovered in the first half of January 1969, it will be designated 1969 A, in the second half of January 1969 B, etc. But in 15 days a number of asteroids can be discovered. Therefore another letter of the alphabet (in sequence of discovery) is attached to the designation mentioned. For example, three asteroids discovered in the second half of January 1969 must be given the preliminary designations: 1969 B, 1969 BB, 1969, BC.

In addition to this general system of denomination, private names are also used, given by the observatory in which the discovery took place. A final designation, i.e., ordinal number and name, is given to the asteroid only after its orbit has been reliably calculated.

This includes one significant difficulty. As long as asteroids were numbered in units, computation of their orbits and ephemerides (i.e., position in the sky for every moment of time in the future) was left to individual enthusiasts. But quite rapidly this task became too extreme for them, and from the lack of knowledge of orbits (and consequently of ephemerides) the small planets discovered were lost again. As already discussed, this unpleasant situation began with Ceres. But at that time, Gauss saved the situation, while later more and more frequent analogous episodes were far from having the same favorable outcome. The examples have a discouraging look.

In the five-year period from 1871 to 1875, 45 of 47 planets discovered received final designations. But already in the first five-year period of the new century (1901-1905) 179 of 300 small planets discovered were lost, and in 1936-1940 only 138 items out of 1,176 small planets discovered were duly recorded!

If the position of a new asteroid was recorded in the sky only once or twice, it may be considered as hopelessly obliterated in the stellar diffusion of dim stars. Even in 1953, as I. I. Putilin has mentioned, the number of such asteroids exceeded 3,500 (i.e., almost two and one half times as many as have been definitively registered)! /14

For the purpose of overcoming these difficulties, the Berlin Computing Office, in existence up to 1945, was created in 1873, essentially as a center for studying small planets. After the war this role was taken over by the Leningrad Institute of Theoretical Astronomy (ITA, founded in 1920) of the Academy of Sciences of the USSR. Observatories of the entire world use the ephemerides[2] published by the ITA. In spite of the application of new computational methods and the widespread use of computers, the problem of losing newly discovered asteroids is still far from solved.

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[2]An ephemeris is a table in which the position of a celestial body in the firmament is shown for different time periods.

In the history of the study of small planets, the year 1891 records the first use of photography in this field. The photographic method, suggested by Max Wolf, considerably facilitated and simplified the observation of small planets. However, individual astronomers had earlier (e.g., 1886) successfully applied photography in locating lost asteroids.

Wolf, and other investigators of small planets after him, began to systematically photograph the plane of the ecliptic[3] with the aid of short-focus illuminating cameras, astrographs. Attached to parallactic supports and moved by clock mechanisms, these cameras reproduced large areas of the sky. Stars were found on the negative as small circles of greater or lesser dimensions, while an asteroid traveling against their background during the exposure (2-3 hours) drew a short, but very evident, streak on the negative. Discovery became a rather easy matter, and there was a common temptation, after the discovery of one asteroid, to look hastily for others in another part of the sky. As a result the newly discovered small planet would be recorded on one or two photographs which was not enough to determine an exact orbit.

However, this drawback did not prevent the further development of the photographic method. As early as the first five-year period (1891-1895) Wolf and Charlois discovered 90 new asteroids on negatives--a result which speaks for itself. Photography also justified itself in the search for lost small planets, searches which were sometimes crowned with triumph. Now photography is used wherever new asteroids are sought. /15

At the present time, the number of observatories concerned with small planet observation approaches 30. In addition to the ITA there are other computational institutions specializing in this field. In Leningrad, Nikolayev, Tashkent, Kiev and other cities, the job of observing small planets is being carried on to a significant degree with the assistance of electronic computers. Successful television observations have been made of some asteroids, at which time it was not eyes that received the radiation captured by the telescope, but a television tube (orthicon).

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[3]The apparent annual path of the Sun against the stars is called the ecliptic.

Russian and Soviet scientists have made noteworthy contributions to the study of the small planets. Even at the beginning of the last century, V. K. Vishnevskiy in Petersburg observed Ceres and Juno. In the second half of the century a considerable quantity of observations of the small planets, of their apparent brightness and position in the firmament, was received at the Moscow and other Russian observatories. The asteroid Eros (to refine the distance from the Earth to the Sun) was photographed in the Tashkent Observatory at the beginning of this century.

Systematic observations of the asteroids began to be made in 1912 in the just-established Simeis Observatory. Their position in the sky was fixed by photography, thus facilitating computation of orbits and ephemerides. These investigations were continued successfully in the Soviet era, also, up to 1941. Many new small planets were discovered, the first of which, discovered as early as 1913 by G. N. Neuman, was given the name 'Simeiz'. Among the discoveries of asteroids in the Soviet Union we should mention the small planet Vladilena (No. 852), named thus in honor of Vladimir Ilyich Lenin.

In addition to the Simeis Observatory, specializing in asteroids, small planets have also been observed in almost all the other Soviet observatories, including the Pulkovo. Parallel with their observations and elaboration, theoretical investigation of the problems connected with small planets (e.g., /16
in the field of theoretical perturbation) has been carried out in many places. A series of astrophysical investigations of asteroids, their color characteristics, changes in brightness and so on, has been set up. The greatest investigations of small planets were carried out by G. N. Neumin, S. I. Belyavskiy and V. A. Al'bitskiy.

The list of asteroids discovered in the USSR is constantly being lengthened. The approval of the International Planetary Center in 1967 confirmed the designations of the last ten new "Soviet" asteroids. Now the catalog of small planets contains the asteroids Chayka (in honor of the first woman astronaut, Valentina /17
Nikolayeva-Tereshkova), Volga, Ukraina, Druzhba, Mirnaya and others. Among these is the asteroid Krao, this being the acronym of the Crimean Astrophysical Observatory. In all, about 1,700 small planets are listed in current catalogs.

In the last century symbols were still being devised for some of them, symbols far less known than those used to indicate the chief planets of the solar system.

METHODS OF STUDYING THE MINOR PLANETS

Two sources are used for studying the small planets--direct astronomical observation and the data from laboratory study of meteorites. In a number of cases combining these two methods has significantly facilitated solution of the problem.

Above all, it is the purpose of astronomical investigation to determine the position of the asteroids in the starry sky as precisely as possible. By solving this problem with methods of current astrometry, we gain data indispensable for computing the orbit of a small planet. Naturally, the result is sometimes not absolutely precise. The cause of this is not only inevitable errors in measuring instruments and the eye of the observer, but also the difficulty of computing perturbations to which asteroids are subject, particularly in regard to Jupiter and Saturn.

Refinement of orbits is achieved with the method of successive approximations. When a new asteroid has been discovered, an attempt is made to get a sufficient number of observations to compute a preliminary orbit. Later this orbit is improved by using a maximum number of observations referring to different parts of the small planet's orbit. In computing the improved orbit consideration is given to the perturbations in the direction of the large planets, predominantly Jupiter and Saturn. It is natural that the ephemeris, computed according to the preliminary orbit, deviates to a greater or lesser degree from the data of the new observations. But the magnitude of these deviations serve precisely as a basis for defining exact orbits.

Two methods can be used to determine the position of an asteroid in the sky--apparent and photographic. The first of these, once the only one, is sometimes used in modern practice. The gist of this method consists in the fact that /18
a micrometer, attached to the refractor at its prime focus, is used at a given moment of time to measure the distance between "guide" stars and asteroids and the difference in their coordinates on the celestial sphere.

Figure 3. Astrograph at the Simeis Observatory.

In the field of vision of the refractor, equipped with a cross-haired micrometer, the observer sees the guide star, the star-shaped small planet and two threads, one immobile and one mobile. With the first of these superimposed upon the star, the mobile thread is moved (with the help of a drum) until it is superimposed upon the asteroid. By following the scale on the drum, the observer finds the distance between the star and the asteroid by angulation.

Let us note that the micrometer can also revolve around the optical axis of the refractor. For this purpose it is equipped with a device called a positional ring. According to the reading on the scale of the positional ring, the observer determines the positional angle[4] of the arc of the major circle going through the asteroid and the star. To sum up, the position of the asteroid becomes known in terms of the star. If one knows the coordinates of the star, it is not difficult to calculate the coordinates of the asteroid.

The visual method is now used as an exception. It obviously cannot meet the competition of the photographic method which enjoys a series of advantages from photographic plates as opposed to the eyes.

[4]The positional angle in a given case means the angle between the arc of the large circle connecting the star and the asteroid and the circle of inclination passing through the star. It is determined from 0° to 360° counterclockwise from the direction of the North Pole of the Earth.

In the past when an observer discovered an unknown starlet in the sky, he needed no less than two or three evenings to clarify what the object might be, asteroid, comet or new star. To fix the new asteroid with modern high-speed cameras requires some 10 to 20 minutes.

In addition, a large area of the sky is fixed on the photographic plate and, if traces of more small planets are found on it, the film records their movement just as easily as the movement of one planet.

Every negative is an excellent document. The observer can make a mistake in measurements and his evaluation thus remains erroneous. It is possible to return to the negative time and again to repeat a measurement. Celestial events are recorded by the photographic film forever and cases are not rare where objects of interest have been found on old negatives tens of years after /19 observation.

In contradistinction to the eye, the photographic plate gradually accumulates the light energy striking it from stars. Its sensitivity is strengthened by extended exposure (naturally within certain limits). Therefore, the longer the exposure, the better a dim asteroid is imprinted upon the negative.

But even on the best negatives there is always a chance of occasional defects. Sometimes they are very insidious: some chance mark can be taken as a small planet. In order to prevent this a double astrograph is used, two cameras photographing the sky at the same time. If a suspicious object is seen on both films at the same time, it is a reliable sign that a celestial object has been imprinted.

Astrographs, telescopes specially adapted for photographing the sky, are used for photographic observations of asteroids. An astrograph is provided with a clockwork which gives it a rotation opposed to the rotation of the Earth. Pointed toward any spot in the sky, the astrograph will "look" at it for as long as desired. Light from any star will fall upon one and the same spot of the plate and the reproduction of this star will look circular. Asteroids, however, move against the background of the stars and their reproduction takes the shape of a dash. This, the oldest and simplest method of photographing asteroids, is called the Wolf method. It is used in photographing bright asteroids.

Another method suggested by Metcalf is often used to observe small dim planets. The clockwork of the astrograph can be regulated in the same way, but not for the astrograph to move along with the stars, but rather with the asteroid to be observed (of which the angular velocity is known). Then the asteroid appears circular on the negative, while all the stars are represented by dashes.

With Metcalf's method exposure can be extremely long, and this means that by accumulating the radiation energy of the asteroid the photographic plate can register very dim objects. However, when Wolf's method is used, the asteroid's reproduction is stretched out in a line which is simply imperceptible for dim asteroids.

The method suggested by the famous Soviet astronomer S. N. Blazhko is very /20 original. Three exposures at intervals of 5 to 15 minutes are taken on one and the same plate. Just before each new exposure the photographic plate is changed a trifle in inclination (e.g., by one minute of arc). It is not difficult to grasp what the negative will show. Every star will give three images, with each image being lengthened out into "chains" parallel to one another (Figure 4). As far as the asteroid is concerned, it will also provide three images but, because of the motion of the asteroid in respect to the stars, the "chain" of images of the small planet will distinguish itself by its unusual slope in comparison with all the other "stellar chains."

As we have already discussed, asteroids are objects imperceptible to the naked eye. The brightest of the asteroids is Vesta. At the most favorable times, i.e., at its maximum approach to Earth, this small planet has a stellar /21 brightness of 6.5 stellar magnitude ($6^m.5$) and can be observed with binoculars. Not far behind it in magnitude are Ceres ($7^m.4$), Pallas ($8^m.0$) and Juno ($8^m.7$). But the majority of asteroids are objects of the 13th and 14th magnitudes, perceptible only with moderate telescopes.

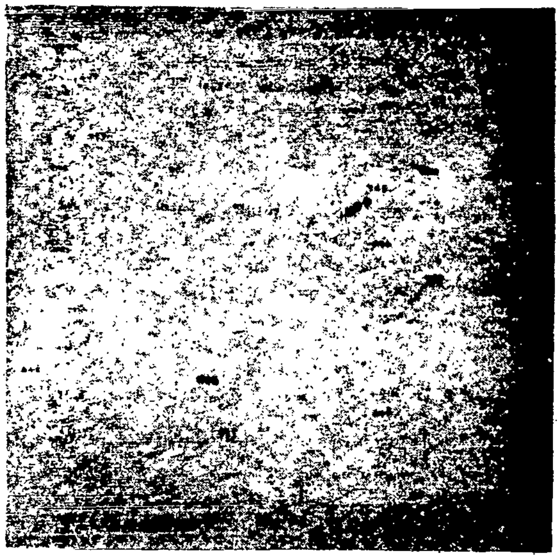

Figure 4. Photograph of the Asteroid Hebe Taken by S. N. Blazhko's Method.

The most expedient astrograph for photographing small planets will be a high-speed and, at the same time, sufficiently long-focus astrograph. The aperture ratio[5] guarantees the sharpness of the image. The greater the diameter of the objective,(for one and the same focal distance), the greater penetrating power the astrograph will have, i.e., the better dim objects will leave their images on the negatives. On the other hand, the greater the focal distance of the objective, the greater will be the linear dimensions of the image. For this reason the movements of the asteroids are perceived easier on films from long-focus astrographs than on films from short-focus cameras. Figure 5 shows the double astrograph of the Heidelberg (Germany) Observatory at which the first photographic observations of asteroids were carried out as early as 1891.

Just imagine that a print has been made and a negative obtained in the laboratory. It is first given a preliminary treatment for the purpose of developing all the images of small planets recorded on it. This can be done in different ways, e.g., by attentively examining the plate in a small microscope of low magnification.

After two negatives of one and the same sector of sky have been taken at nearly the same time, a stereocomparator or a blink comparator is usually used.

The operational principle of the first of these instruments is quite simple. A portion of the stellar sky imprinted upon two negatives taken at

[5]The square of the ratio of its diameter to the focal distance is called the aperture ratio of the lens (or of the lens system).

different times is looked at uniformly and the only difference will be in the positions of the asteroids fixed on the plates. If we use the stereomicroscope, the basic part of the stereocomparator, to superimpose the optical images of two negatives, the images of the stars on it will fade, while the small planet will appear to the observer as if it were hanging in space, because of the stereo-effect.

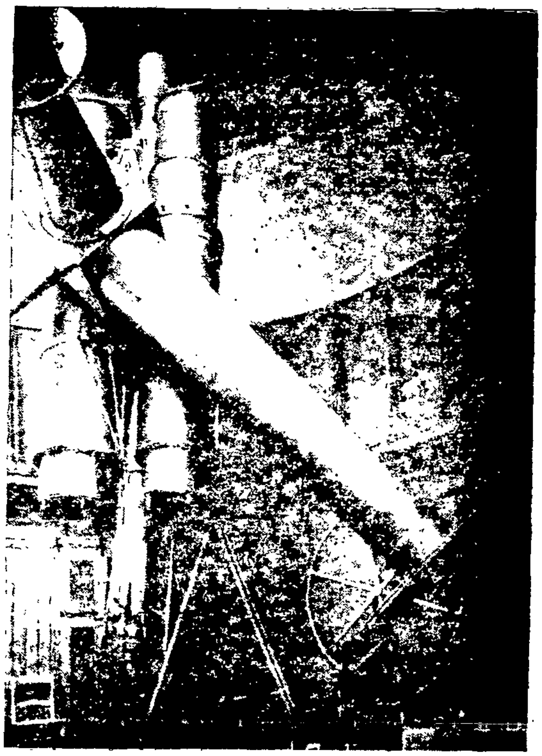

Figure 5. Double Astrograph of the Heidelberg Observatory.

With the blink comparator a special blink microscope introduces two images of the negatives into one ocular. A special sliding screen makes it possible to see one or the other plate. If the screen is moved quickly, we get a curious effect: the image of the asteroid will jerk in the field of vision, while the images of stars remain motionless. /22

When an unknown small planet is discovered, its position among the stars is recorded on a large scale stellar chart, an approximate determination of its coordinates is made, /23 and the Leningrad Institute of Theoretical Astronomy is informed of the discovery made. Publication of the event is made in *Astronomicheskiy Tsirkulyar*, put out by the Academy of Sciences of the USSR, and in the publications of the Observatory in Cincinnati (USA).

Further precise treatment of the photographs of small planets includes as thorough measurement as possible of the position of the asteroid on the negative in reference to known stars. For this purpose, special high precision measuring devices are used. In all of these structural variations, the purpose of the instruments is identical, to measure as exactly as possible the position of the asteroid on the negative and then to determine its coordinates against the firmament.

Astrophysical observation of the small planets (not counting evaluations of their apparent brightness) have been rare and haphazard up to this time, not subject to any one program. In the meantime, observations of the refractive capacity, color and spectrum of asteroids have been particularly valuable in revealing their physical properties, without which it is impossible to explain their relationship to the other bodies of the solar system and to solve the problem of their origin.

Even an evaluation of the apparent brightness of asteroids can be a source of extremely valuable information. Although asteroids cannot be distinguished outwardly from stars with binoculars, the simplest determination of their apparent brightness can be made just as for variable stars.

Such observations are within the reach of every amateur astronomer who is equipped with binoculars or a telescope. With sufficient skill in observation, they have a definite scientific value. More exact measurement of asteroid brightness can be obtained by using special photometers, such as are used for investigating the variable stars.

The brightness of asteroids is not constant. It depends, not only on their distance from the earth, but also on other factors, for example on the rotation of the asteroid and on its fragmentary form.

In visual observation with the telescope, the eye cannot distinguish differences in the color of asteroids. However, it is possible to evaluate such an important characteristic as the color of a small planet by using photographs (Figure 6).

As is known, the eye is more sensitive to yellow and green rays, while a photographic plate is more sensitive to blue and violet. It follows from this /24
that evaluations of stellar brightness by apparent and photographic observations, generally speaking, are perceived differently. For example, the "photographic" stellar magnitude of red stars is always less than the "apparent" stellar magnitude. The effect is reversed for blue stars.

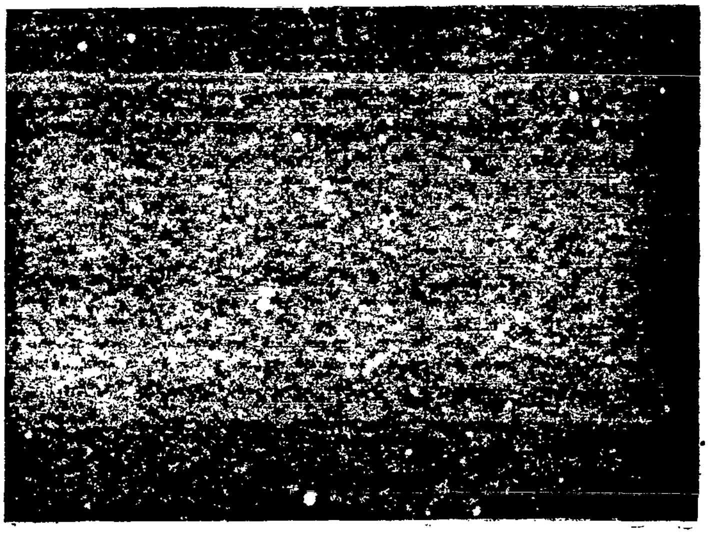

Figure 6. Photograph of an Asteroid Track.

The difference between photographic and apparent stellar magnitudes is called the color index of a given heavenly body (for more details see page 47.) For white objects, the color index is close to 0, for blue ones it is negative, and for yellow, orange and red ones it is positive. The color indexes of asteroids are essentially different, and this circumstance is undoubtedly related to their physical nature, their composition and structure.

Even more valuable information on this question is provided by spectral observations. They were begun as early as 1874 by Vogel, but their later use was haphazard, from case to case. The reason for this is partially the wide- /25 spread erroneous belief among nonspecialists that the spectra of all asteroids are only faint copies of the solar spectrum. Actually this is not the case. In a number of cases the small planets are not at all simple reflectors. Even Vogel noticed in the spectrum of Vesta mysterious bright lines of radiation. It is true that this is an exceptional case, but on many other small planets there have been observed other spectral peculiarities, not always understood and not even analyzed; we shall speak more of this below. Spectral observation of the asteroids should be widely adopted and developed, and may prove to be decisive in solving a number of problems.

Completely new in both form and essence in the near future will be "astronautic" observations of asteroids. Devices flying in space and allowed to drift in the region of the asteroid belt could transmit valuable information to

Earth. For example, space devices "Mars-1" and "Mariner-4", in their flight to Mars, intersected the orbit and recorded the existence of previously unknown streams of meteors. In the more distant future it is not inconceivable that the crew of a spaceship will land on the larger of the asteroids.

THE MOTION AND ORBITS OF THE ASTEROIDS

The apparent displacement of asteroids in the firmament, just like the large planets, is caused by two factors--genuine movement of the small planet in space and the orbital movement of the Earth. A combination of these two motions, as known, leads to planets describing intricate loops in the sky. Their direct movement--from west to east--sometimes reverses, and vice versa. The loop-forming shifts of the planets are observed during periods of their opposition.

In the majority of cases, the apparent movement of the asteroids differs little from the apparent movements of, let us say, Mars or Jupiter. However, there are curious exceptions. In those cases where the orbital plane of a small planet is inclined by a considerable angle to the plane of the terrestrial orbit, the apparent movement of an asteroid can be quite peculiar. Such, for example, is the apparent route of the asteroid Ganymede through the sky. As a rule, this small planet can move 10° from the ecliptic, and in special cases /26
Ganymede has even passed close to the pole of the ecliptic, behavior which is impossible for the large planets.

As stated already, the method of Gauss permits the orbit of a heavenly body to be calculated from three observations, particularly that of a small planet. Let us explain the main principle of this method.

Every elliptical orbit is characterized by six magnitudes, named its elements. The location of the orbital plane of a planet is fixed by two angles: the orbital inclination i, i.e., the angle formed by the orbital plane of the planet with the orbital plane of the Earth and the longitude of the ascending node Ω, i.e., the angle between a line from the center of the Sun to the position of the vernal equinox γ (the point in the sky where the Sun is found about 21 March) and the line intersecting the planes of the terrestrial and planetary orbits.

The form and dimensions of the planetary orbit depend on two other elements--the semi-major axis a and eccentricity e. The position of the orbit in its plane can be found by knowing the distance of perihelion from the node--angle ω, formed by the line intersecting the terrestrial and planetary orbit with a line from the center of the Sun to perihelion[6] of the planetary orbit. Finally, the position of the planet on its orbit can be known if the moment the planet passes through perihelion T is known.

Every observation of an asteroid gives its angular coordinates in the sky. It is possible to form three equations relating these coordinates to the orbital elements of a planet. However, it is inevitable that one more unknown enters these equations, the distance of the planet from the Earth. Consequently, one observation will give three equations with seven unknowns. The second observation produces still another unknown--the new distance between the asteroid and the Earth. This means in sum that we shall have six equations with eight unknowns. Finally, after the third observation, we get nine equations with nine unknowns, i.e., a system which permits a unique solution.

This is the theoretical side of Gauss' method. Although a large number of attempts have been made to improve Gauss' method, all have been limited to only an improvement in detail, while the method remains as it was.

If we prescind from reality, from the extremely complex situation, and consider that only the gravity of the Sun affects an asteroid, the asteroid's orbit in any given case, as Isaac Newton has already shown, will be a conic section--an ellipse, a hyperbola or a parabola. In actual fact the attraction of Jupiter, Saturn and other planets proves to have a substantial influence on the movement of an asteroid. For this reason the orbit determined by Gauss' method is essentially only a first approximation to the real shape of the planetary orbit. Further refinement of the orbit includes consideration of the perturbations on the part of a possibly large number of large planets. It is natural that long series of observations, of high quality and lasting many years, are required for this period. /27

[6]Perihelion is the point of an orbit closest to the Sun, and aphelion is the point most distant from the Sun.

In this field there are peculiar records. For example, the orbital elements of Juno were determined by computing the perturbations of all the large planets (excluding Pluto). The orbit was found for Ceres, the largest of the asteroids, by taking into account perturbations on the part of Venus, Earth, Mars, Jupiter and Saturn. Considerable improvement in the orbits of many other small planets has also been obtained.

What are the orbital features of small planets? How is is possible to represent the structure of the asteroid belt or ring in general diagrams (Figure 7)?

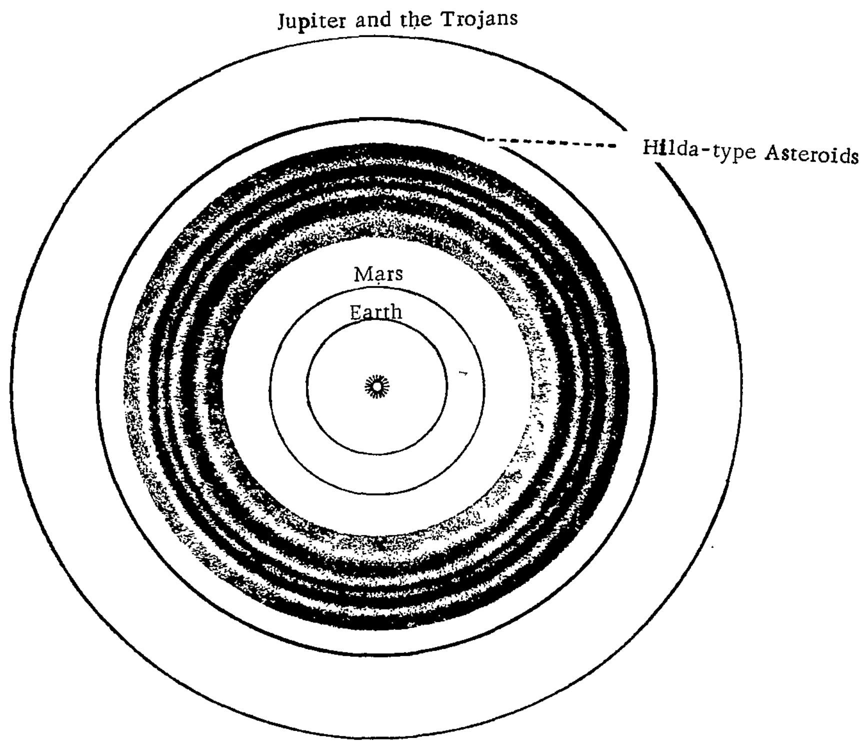

Figure 7. Structure of the Asteroid Ring.

With rare exceptions, the orbits of the asteroids are located between the orbits of Mars and Jupiter. Besides this about 97% of the small planets possess a semi-major axis restricted to still narrower limits--from 2.17 to 3.64 AU (let us recall that the semi-major axes of the orbits of Mars and Jupiter are close to 1.5 and 5.2 AU, respectively.)

The elliptical orbits of asteroids have different elongations and eccentricities[7]. For example, 98.7% of the orbits of known asteroids possess eccentricities less than 0.33. The average value of eccentricity for all orbits found amounts to 0.15. Consequently, although the orbits of asteroids are more elongated than the orbits of the major planets, the majority of asteroids revolve in orbits which are not far from circular. It is surprising that the smaller the asteroid, the more elongated its orbit, a regularity to which we shall return later.

All of the major planets, as is known, move in almost a single plane. Only Mercury and Pluto have an orbital inclination i equal to 7 and 17°, respectively. /28

In this respect, the orbits of asteroids possess an interesting peculiarity. Even the mean value of their orbital inclination exceeds 9°. In special cases, such as the asteroid Hidalgo (Figure 8), inclination reaches 42°. Even in such an important asteroid as Pallas, orbital inclination is close to 35°. From this we can draw the conclusion that the asteroid belt is "flattened" into one plane to a far lesser degree than the orbits of the major planets.

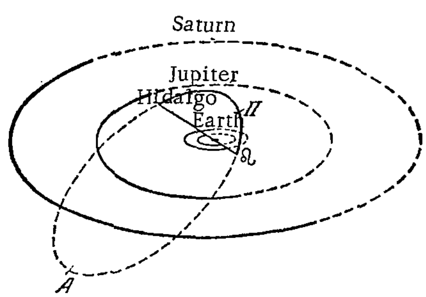

Figure 8. Orbit of the Asteroid Hidalgo.

The orbits of asteroids are unevenly distributed in space. The asteroid belt is by no means continuous. Observations of it show holes and gaps, to which attention was first called by D. Kirkwood in 1866. The gaps are located in very definite portions of interplanetary space, namely at the spot where conditions are met for so-called commensurability. /29

Let n be the mean daily movement of a small planet. This magnitude can be determined by the equation

$$n = \frac{k''}{a^{3/2}},$$

[7]The ratio of the distances between the focal points of an ellipse to the length of its semi-major axis is called an eccentricity of the ellipse. The more elongated the ellipse, the greater the eccentricity.

where a is the semi-major axis of the asteroid orbit and k" is some constant expressed in seconds of an arc. The ratio of mean motion of the perturbing planets and of the asteroid, expressed as a simple fraction, is called commensurability. In other words, if n_1 is the mean motion, e.g., of Jupiter, and n is the mean motion of the asteroid, commensurability is $^{n_1}/_{n} = {}^{p}/_{q}$, where the ratio of the two reciprocal whole numbers is found on the right side of the equation.

As a rule, gaps in the asteroid belt are found in those places where (for corresponding a) commensurability of daily motion of asteroids and Jupiter or Mars is observed. It can be shown that in these areas of space perturbations become very strong and these perturbations finally pull the asteroid into more "peaceful" zones. Observations show that in those parts of the asteroid belt, where commensurability with Jupiter equals, e.g., 1/2, 1/3, 2/7, 5/11, etc., there /30
really are vast and noticeable gaps. There is even one gap generated by Mars. It corresponds to a commensurability of 2/1. It is possible to distinguish seven rings in the asteroid belt, distinguished by tangible gaps.

However, there are not gaps for all commensurabilities. With an increase in the number of asteroids discovered, the number of gaps is gradually filled. On the other hand, instead of gaps there are aggregations of asteroid orbits in some commensurabilities with Jupiter (e.g., 2/3).

The most complete study of gaps was carried out by the famous Japanese investigator of asteroids, K. Hirayama. Assuming that the asteroids move in some resistant medium (a cloud of small fragments of constantly disintegrating asteroids), Hirayama was able to explain in theory the existence of both gaps and aggregations.

Among the more than 1,500 asteroids known at the present time there are sometimes found pairs with almost identical orbital elements. Such are the asteroids Ingrida and Azaliya, Lobeliya and Kapanula, Juno and Cloto.

Some groups of asteroids with close orbital elements are more numerous. The Trojan group, important asteroids revolving around the Sun in almost the orbit of Jupiter (they will be discussed in more detail later), consists of 15 small planets.

The compact group of asteroids of the Hilda type is interesting. It includes 19 small planets having almost identical orbits and almost borders the asteroid belt on the outside.

Hirayama introduced the concept of "asteroid family", an association of small planets of common origin. In order to pick out such families, Hirayama used the so-called features of orbital elements, i.e., those elements whose magnitude does not change during the movement of the asteroids independently of perturbations on the part of other planets. If asteroids belong to one family, they must have similar features in their elements.

Let us explain Hirayama's concept with a simplified example. Imagine that a large asteroid has broken up into a series of fragments (e.g., from collision with other asteroids). In this case the orbits of the fragments will be distinguished by one remarkable quality: they will all pass through the point where /31 the asteroid exploded, forming a class of ellipses. This feature leads to the conclusion that the currently existing fragments once composed a single entity.

In actuality everything is more complex. Perturbations on the part of Jupiter and other planets eventually destroy the classes of orbits, and the traces of the catastrophic explosion of the large body into small fragments "disintegrate" with time, become lost and are difficult to find.

Nevertheless, Hirayama succeeded in reliably pointing out five asteroid families with almost identical features in their elements. Later, in 1925, the Soviet investigator, N. M. Shtaude separated 15 more families, naturally less clearly marked.

G. F. Sultanov and other investigators made successful attempts at distinguishing the families of small planets, not according to the similarity of the features of their elements, but according to other parameters. The results turned out to be similar to those obtained by Hirayama.

All of this can lead to the conclusion that groups and families of asteroids are obviously products of the disintegration of some larger, ancestral bodies. The number of asteroids in the present era is so great that collisions between them are not only possible but evidently occur constantly during the evolution of the asteroid belt. It is not an exaggeration to say that the asteroid zone is a zone of gradual mechanical disintegration and degradation of celestial bodies. Reciprocal collisions of asteroids lead to their degeneration, to an accumulation of a powdery resistant medium in the asteroid belt composed of smaller fragments of gradually disintegrating asteroids.

IMPORTANT ASTEROIDS

Exceptions, as known, do not only prove the rule but also attract attention to themselves. Those asteroids which have unusual orbits, i.e., which are distinguished from the overwhelming majority of small planets by this trait, are considered important (a term which naturally has no claim to being official). We shall acquaint the reader with only a few of the important asteroids.

The Trojans /32

Let us assume that at some time we knew the position of three bodies in space and their initial velocity. We shall consider these bodies as material points, i.e., we shall disregard their dimensions in comparing distances between them. Considering the fact that reciprocal attraction exists among these three material points, we shall find the trajectory, velocity and acceleration of all three bodies for any moment of time.

The formulation of the problem in this way has been given the name *the three-body problem* in celestial mechanics. In 1912 K. Sundman, an outstanding Finnish mathematician, solved this problem in a general way. However, his solution has only purely theoretical interest. The coordinates of three bodies in Sundman's solution are represented as a series ("of infinite sums"), very complex and difficult to use in calculation. For example, in order to compute the coordinates of bodies for two months in the future with a precision of 10% (for the sake of simplicity let us assume that the masses of the three bodies and the mutual distances between them are equal), it is absolutely necessary to take a number greater than $10^{80,000}$ for the members of the series.

An exact and relatively simple solution of the problem of three bodies was found by the eminent French mathematician, J. Lagrange as early as the end of the 18th century, although only for some special cases.

Let us imagine that one body revolves around another in a circle. As Lagrange showed, there are certain positions of the third body at which the mutual arrangement of all three bodies during movement remains unchanged.

Let the first body be the Sun and the second a planet revolving around the Sun in a circular orbit. The points at which a third body maintains a reciprocal arrangement in relation to the other two bodies are called libration points. The first three of these, so-called colinear libration points L_1, L_2 and L_3, spread along a straight line, pass through the Sun and the planet. Their arrangement on this line naturally depends upon the masses of the first two bodies and the distance between them. If a third body is located at any of these points, the entire system, made up of three bodies, will rotate as a single body (just as if you were to rotate a picture around a point). However, research has shown that the location of the third body on colinear libration points is /33
unstable. If this body even very slightly, no matter how small the distance, leaves the colinear libration points, it can never return but must abandon this area of space forever. Therefore it is not surprising that a "Lagrange case" exists in nature.

Triangular libration points L_4 and L_5 have an incomparably greater practical importance. With the Sun and the planet, they form the apexes of two equilateral triangles turning together as a single entity during movement. It is surprising that motion near these points is stable, as thoroughly substantiated in the work of V. I. Arnold[8] and other researchers. In other words, if it is pulled from the triangular libration points, under certain initial conditions the third body can again return to its original position.(e.g., if its velocity is not excessive).

In 1907, the asteroid Achilles (No. 588) was discovered revolving around the Sun almost in Jupiter's orbit. More exactly, it is always found close to point L_4 in the Sun-Jupiter system. Later, other small planets were discovered which demonstrated one of the "Lagrange cases" in nature itself. They were all given names of heroes of the Trojan War, and therefore in astronomical literature these important asteroids are called the Trojans (Figure 9).

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[8]See reference [3].

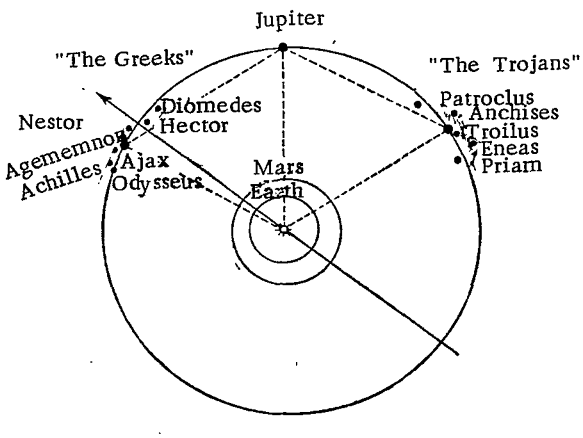

Figure 9. The Trojan Asteroid Groups.

Fifteen of them are known. Ten of them (Achilles, Hector, Nestor, Agamemnon, Odysseus, and others) move in front of Jupiter, leaving it behind at a longitude of 60°. The five others (Patroclus, Priam, Eneas, Anchises, Troilus) follow Jupiter and remain in the vicinity of point L_5. Properly the first ten of the asteroids mentioned bear the names of heroes of the Greek Army and therefore are sometimes called "The Greeks" (in contradistinction to the real "Trojans" following Jupiter). However, this amusing distinction does not enjoy general acceptance.

Not a single one of the Trojans is exactly at one of the triangular libration points. On the other hand, the orbit of Jupiter is not an ideal circle, but an ellipse with eccentricities amounting to 0.05. A conjunction of these two factors leads to the fact that each of the Trojans carries out its /34 complex, periodical motion around libration points L_4 and L_5 while simultaneously revolving around the Sun. Some of the Trojans sometimes wander quite far from the libration points, e.g., Anchises to 28° and Diomedes even to 40° (in longitude)! Even the minimum distance of the Trojans from the libration points is never less than 5°.

The Trojans are major asteroids. The largest of them, Patroclus, has a diameter of 272 km. Shortly behind it comes Hector (diameter 216 km), with eight more Trojans having diameters greater than 100 km.

It is curious that the Trojans are not a unique natural illustration of the particular case of the problem of three bodies. In 1959 the Polish astronomer Kordylewski observed extensive clouds of small cosmic dust near the triangular libration points of the Earth-Moon system. Only on very clear dark nights and under favorable moon conditions were these clouds of Kordylewski able to be observed as diffuse dim patches. It is obvious that thousands of small particles of interplanetary cosmic dust, imprisoned in stable orbits by the joint attraction of the Earth and of the Moon, play the part of the Trojans here.

Eros /35

Even long before the discovery of the Trojans, 13 August 1898, an unusual asteroid was observed in the Berlin Observatory. Judging from the negative, this small planet passed through a celestial path each day equal to the apparent diameter of the Moon. We now know of far more striking examples, but at the end of the last century this case was very exceptional.

When the orbit of Eros (as they named the unusual asteroid) was calculated, it seemed that its larger part was located within the orbit of Mars. Its position at perihelion was found equal to 1.13 AU, and at aphelion to 1.78 AU, and its orbital inclination close to 11°.

More striking was the fact that during maximum approach of Eros to Earth the distance between these two celestial bodies was reduced to 23,300,000 km. In other words, Eros became the closest celestial body to the Earth, after the Moon.

The "year" of Eros extends for 1.76 earth years. It can be calculated that great oppositions of Eros (i.e., its closest approaches to Earth) are repeated in 37 and 44 years. When one of these took place in 1931, Eros approached the Earth to a distance of 26,000,000 km, an event which was not only interesting but also useful. We shall explain later what we mean here.

As is known, the relative distances of planets from the Sun (i.e., the ratios of the semi-major axes of the planetary orbits to the semi-major axis of the Earth's orbit) can be obtained directly from observation. Imagine, for example, the opposition of Mars. It takes place when Mars culminates at local midnight, a fact found by observation. For a month the reciprocal disposition of the Sun, Earth and Mars changes. Instead of being arranged on a single straight line, they now form the apexes of some kind of triangle. Here the angle at the Sun is known, equal to the differences in arc passing through the

Moon and Mars along their orbits (we shall consider them circular for the sake of simplicity). The arcs are easily determined by the rotational periods of the Earth and the planets derived from observation.

The angle at the Earth between a line to the Sun and a line to Mars is called elongation, and it is found according to the position of the Sun and Mars in the sky. In this way, by looking at the triangle, all angles[9] are known, and this means (according to the theorem of sines), that the ratio of the radii of the orbits of Earth and Mars can be found: /36

$$\frac{MS}{ES} = \frac{\sin \angle MES}{\sin \angle EMS} .$$

This fact is extremely noteworthy. It explains how Kepler was able to formulate his third law of planetary motion by joining the distances of the planets from the Sun with their periods of revolution, without knowing what these distances were. This all depends upon the fact that in Kepler's third law

$$\frac{T_1^2}{T_2^2} = \frac{R_1^3}{R_2^3}$$

(the squares of the times of planetary revolution around the Sun are proportional to the cubes of their distances from it), the absolute distances of the planets do not play a part (they were first measured in the 19th century), but rather the ratio of these distances. This means that Kepler knew, so to say, the proportions of the planetary orbits and he was able to correctly illustrate them in a diagram, but without indicating their scale.

It follows from this that if the distance of any planet to the Sun can be measured, the "scale unit" will be found and all other distances in the solar system can be obtained as the sum of simple computations.

The approach of Eros to the Earth is an excellent opportunity for solving this problem. By observing Eros from different observatories, quite far removed

[9] The apex of the triangle coinciding with the Sun is designated by the letter S, with the Earth by E, and Mars by M.

from one another, at one and the same moment of time, it will be possible to measure its apparent displacement on the background of the stellar sky. The starry appearance of Eros will favor a highly exact measurement. By determining the distance from Eros to the Earth, it will be possible to refine the magnitude of the astronomical unit, the mean distance from the Earth to the Sun, the main "scale unit" in astronomy.

Eros was the first of the small planets whose observation helped tangibly in refining the magnitude of the astronomical unit. Later, other asteroids passing by the Earth were also used for this purpose. At the present time, all of these means have become antiquated and have given way to the method of radio location for determining distances from planets.

An unusual oscillation in brightness also attracted attention to Eros. /37
First noticed in 1901, these oscillations have been the object of study of a number of astronomers. To all appearances they are related to the physical nature of Eros, but the peculiarities of its shape and structure are not yet fully clarified.

Ganymede and Its Group

The asteroid named Ganymede[10] was first observed 23 October 1924 at the Bergerdorf Observatory. A remarkably apparent brightness upon discovery (9.5 stellar magnitude) and an unusually rapid apparent movement distinguished this small planet from others. Its direction of movement, directly from east to west, in contrast to retrograde motion, which the majority of asteroids have, was almost unique. By its eccentricity (0.542) and inclination (about 26°) /38
the orbit of Ganymede was reminiscent of the orbit of a comet with a short period (Figure 10).

Two other asteroids--Albert and Alinda--are known to have orbits with similar characteristics. It is noteworthy that they can pass comparatively close to the Earth, e.g., in 1924 the minimum distance between Ganymede and the Earth amounted to 0.5 AU. However, in this connection there

[10]The largest of Jupiter's satellites also bears the name Ganymede.

are still more remarkable asteroids. The main property of small planets of the Ganymede type is the extreme elongation of their orbit, "comet-like".

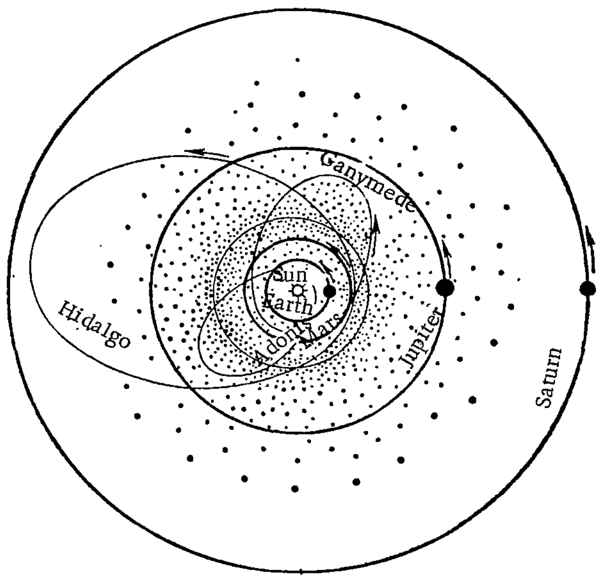

Figure 10. Orbits of Some Important Asteriods.

Hidalgo

This unique asteroid, discovered in October 1920, has two exceptional qualities: the semi--major axis of its orbit is 5.8 AU, and its orbital inclination is about 42°. In other words, compared with the other small planets, the asteroid Hidalgo revolves around the Sun in the orbit which is largest and most "inclined" toward the ecliptic. If this angle of inclination were close to zero, Hidalgo would approach Saturn; because of its great eccentricity (0.66) the distance of Hidalgo from the Sun varies from 1.9 to 9.7 AU! However, thanks to the considerable inclination of its orbit, the minimum distance from Hidalgo to Saturn is never less than 5.7 AU. It is a matter of curiosity that Hidalgo's "year" equals 13.7 terrestrial years, the only such case we know of among the asteroids.

It is assumed that around the year 1130 Hidalgo came quite close to Jupiter which sharply changed its original orbit because of its powerful attraction. However, what the orbit could have been is not clear in its details.

Amor, Apollo, Adonis and Hermes

All of these small planets are united by one feature: in their flight around the Sun they can sometimes approach quite closely to the orbit of Earth. In fact, it was this situation which led to the discovery of Amur, Apollo, Adonis and Hermes; at long distance, these small planets with diameters on the order of 1-2 km would simply have remained unnoted.

Amour and Apollo were discovered in 1932, Adonis in 1936 and Hermes in 1937. Of this group the last asteroid, perhaps, is the most remarkable.

At the time of its discovery it almost "flew" through the sky; in one day /39
Hermes moved 90° in direct ascent, cutting through a quarter of the firmament!

The semi-major axis of Hermes' orbit (1.3 AU) differs slightly from the astronomical unit, and at the time of its closest approach to Earth the distance between Hermes and our planet can be reduced to 580,000 km.

Unfortunately, because of ignorance of the exact orbits of Hermes, Adonis and Apollo, they must be considered as irretrievably lost. Only the next meeting with Amour can be predicted beforehand, and this little planet has been observed more than once during the period of its oppositions. Unfortunately, the minimum distance to Amour will never be less than 16,000,000 km.

Icarus

This asteroid could be completely assigned to the previous group. However, its properties are so unique that Icarus should be discussed by itself.

Icarus was discovered 26 June 1949 at the Mount Palomar Observatory (USA). In almost all aspects its orbit proved to be exceptional: eccentricity 0.83, inclination 23°, semi-major axis 1.08 AU (Figure 11).

Revolving around the Sun in a period close to 1 year (409 days), Icarus approaches the Sun at perihelion at a distance of 28,000,000 km, i.e., 30,000,000 closer than Mercury. At this time the surface of Icarus must be heated to a temperature of 500°C, while at aphelion, going beyond the orbit of Mars, Icarus becomes extremely cold.

Such immense changes in temperature can hardly help affecting the physical structure of Icarus. It is most likely that the physical nature of this small planet differs greatly from the nature of the other asteroids.

Icarus is very small--its diameter scarcely exceeds 1 km, and only its closeness to the Earth at certain moments led to its being noticed. Under the most favorable approaches for observation, the distance between Icarus and the Earth is reduced to 6-7 million km.

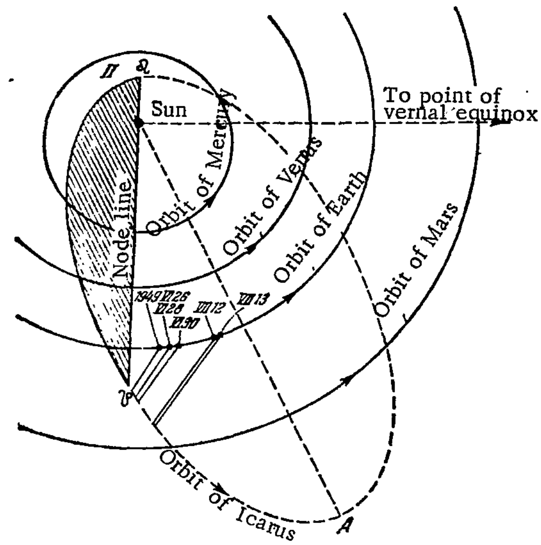

Figure 11. Orbit of the Asteroid Icarus.

Since its discovery, Icarus has been observed during many oppositions. Therefore, its orbit is known well enough to predict meetings of Icarus and the Earth with great reliability.

The next approach of Icarus to Earth occurred in June 1968. On 14 June the distance between them was reduced to 6.4 million km. On this day Icarus looked like a small star of the 11th magnitude, noticeably moving at a velocity of around 1°/hr from the North Star toward the constellation Bootes. Icarus was successfully photographed at several Soviet Observatories (Figure 12). It is of interest that as early as 12 June, Icarus was photographed with the aid of a television system connected with a 2.6 meter reflector at the Crimean Astrophysical Observatory. Absurd rumors, spread several years ago about a collision between Icarus and Earth in 1968 and the catastrophic consequences of this collision, proved to be false, as was to be expected. /40

Icarus is interesting from many points of view in astronomy. In particular its approach to Mercury makes it possible to determine the mass of the latter. The perihelia of the orbit of Icarus, while it is moving in space, make it possible to verify one of the effects of the theory of relativity. Finally, it /41 is not impossible that in the future an automated interplanetary station will be successfully placed on this remarkable small planet. Close observations (not to speak of a landing) can tangibly enrich our knowledge, still very scanty, of the physical nature of asteroids.

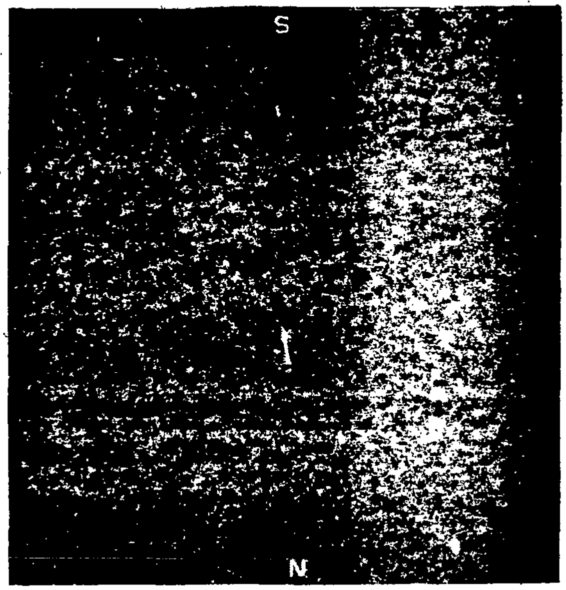

Figure 12. Photograph of the Asteroid Icarus.

THE PHYSICAL NATURE OF THE MINOR PLANETS

Even Gauss and Olbers considered a study of the brightness of small planets an extremely important property in the clarification of their physical nature. Not being luminescent bodies, the asteroids merely scatter the solar radiation incident upon them, thanks to which they can be found for observation.

Two factors chiefly determine /42 the apparent brightness of small planets, i.e., the brightness produced by them at the surface of the Earth. There are, first, the stance distance of the asteroid from the Earth at the moment of observation and, secondly, its distance from the Sun. To speak more concretely, the apparent brightness of a small planet changes in inverse proportion to the squares of the distance to the Sun and to the Earth.

Let us designate the brightness of an asteroid at a distance r from the Sun and at a distance Δ from the Earth by I, while I_0 will mean the brightness of a small planet in relation to the distance r_0 and Δ_0. In this case it is found that

$$I = I_0 \frac{r_0^2 \Delta_0^2}{r^2 \Delta^2}.$$

Here r_0 means the semi-major axis a of the asteroid orbit, Δ_0 is the magnitude a - 1, obviously equal to the distance from the Earth to the small planet at the moment of its opposition.

If, making use of Poisson's well-known ratio

$$\frac{I}{I_0}=2,512^{m_0-m},$$

we proceed from brightness I and I_0 to the corresponding stellar magnitudes m and m_0, the formula mentioned above, after taking the logarithm, assumes the shape

$$m = m_0 - 5 \log a(a - 1) + 5 \log(r\Delta).$$

The stellar magnitude m_0 of the asteroid at the moment of its opposition depends on the dimensions of the orbit of the small planet and, consequently, does not characterize its physical properties. Therefore, it is convenient to use a second magnitude, called the absolute stellar magnitude of the planet. This term means the apparent stellar magnitude which the asteroid would have if it were moved a distance of 1 AU from the Sun and from the Earth at the same time. Here, we presume that the entire lighted half of the asteroid is turned toward the Earth, i.e., that its phase corresponds to a full moon.

It is not difficult to realize that the first two conditions contradict the third. At an equal distance from the Earth and the Sun the asteroid forms with them the vertex of an equilateral triangle, and this means that the asteroid will have a noticeable phase. Therefore the absolute stellar magnitude of a small planet is an abstraction, but very convenient for characterizing the physical properties of the asteroid.

If we posit $\Delta = r - 1$ AU and the designated absolute stellar magnitude of /43
an asteroid with the letter g, we get

$$g = m_0 - 5 \log a(a-1),$$

from which, in consideration of the formula written above, we finally get

$$m = g + 5 \log (r\Delta).$$

In this way, if we know g it is possible to compute the apparent stellar magnitude m of a given asteroid for any distances r and Δ. The reverse can obviously be done, finding g by measuring m, r and Δ.

The greater the absolute magnitude g of the asteroid, the larger it is (other conditions remaining equal!). It is interesting that as g is reduced, the number of asteroids possessing the given absolute stellar magnitude steadily increases. There is no doubt that an immense number of small and very small asteroids are simply not detectable by modern instruments because of their small g.

In order to compute the diameter of an asteroid, taken as a spherical body in the first approximation, it is not enough to know only g. In addition to this, it is necessary to provide a definite albedo, i.e., a magnitude characterizing the reflective capacity of a given asteroid. By albedo we mean the ratio of the amount of scattered planetary light to the amount of light received by it from the Sun. For example, the albedo of the Moon is equal to 0.07. This means that the lunar surface reflects only 7% of the solar radiation falling upon it. In this way the albedo characterizes the degree of blackness of a surface, and it follows from the previous restriction that, let us say, the nature of the lunar surface is very dark, similar in reflective capacity, for example, to such terrestrial objects as volcanic tuff.

Determination of the albedo mentioned is not very exact. In the most exact formulations the law of light dispersion, adopted for a given surface, is considered. However, going into the details and niceties of this rather difficult question is scarcely appropriate here. The physical nature of the albedo is sufficiently clear even if formulations are not extremely strict. How should the albedo be taken in computing the diameters of small planets?

As already mentioned more than once, all known asteroids look like star-shaped objects with visible diameters completely masked by diffraction disks /44
which are too great for their dimensions. Only the first four small planets: Ceres, Juno, Pallas and Vesta, are visible as minute disks in the most powerful telescopes. William Herschel, in 1802 and Schroeter in 1805 tried to inspect these disks. However, it was only 100 years later in 1901 that Barnard, using

the world's most powerful 40-inch refractor at the Yerkes Observatory, reliably measured the visible diameter of the four largest asteroids. Ceres had a disk diameter scarcely greater than 1 second of arc (1".06) and the diameters of the other three were less than 1".

When the visible angular dimensions of an asteroid, its apparent stellar magnitude and its distance from the Earth are known, it is possible to compute its albedo. As this has so far been proved possible for only four asteroids, we are not at all convinced that all other small planets possess such an albedo. Taking the albedo of all asteroids as equal to the albedo of Mars or some other major planet is an example of one solution. The arbitrariness of this condition is obvious, and it is clear from it that the measurements of small planets are still not known by us with the desired exactitude.

What is the distribution of the small planets in regard to their dimensions? Only two asteroids, Ceres and Pallas, have diameters greater than 400 km and only 14 small planets have diameters greater than 240 km. A general regularity is obvious: as the dimensions are reduced, the number of asteroids possessing such dimensions increases regularly. The smallest of the known asteroids, such as Hermes, have diameters measured only in hundreds of meters. There is no doubt that as the sensitivity of telescopes increases there will be found in the not distant future in the depths of space around the solar system tiny planets comparable in dimensions to the largest meteorites. It is difficult to place any limit to the size of asteroids. The constant fragmentation of asteroid bodies leads to the conclusion that there undoubtedly exist in the asteroid belt fragments with diameters in meters, centimeters, millimeters and microns. If then, some particle revolves around the Sun in an elliptical orbit, even if only partially located in the asteroid belt, we have no basis for denying such an object the title "asteroid," no matter how small its dimensions.

However, this is merely a matter of terminology. It is possible to call only those objects of the asteroid belt with diameters, let us say, exceeding /45 100 meters or 1 meter asteroids. But so far such a limitation has not been introduced and therefore discussions about the total number of all asteroids in the solar system remain quite indefinite.

Another problem is the estimation of the total mass of the asteroid belt. This can be solved in several ways.

If we consider the shape of the asteroids to be spherical, it is easy to calculate that the total volume of the first 1,500 small planets is equal to the volume of a sphere with a diameter of 1,340 km, which is almost nine times smaller than the diameter of the Earth. It is interesting that 2/3 of this volume falls to the lot of the largest asteroids (their catalog numbers: 1, 2, 3, 4, 5, 6, 7, 10, 15, 16, 22, 29, 39, 52, 196, 349, 511, 617, 704). Naturally, such an evaluation is only a first approximation toward reality. Only part of the asteroids are considered in it, and even here all the asteroids are considered as spheres, a deliberate fiction.

The result can be made more exact by considering not only the asteroids discovered, but also the ones which are still unknown, with diameters exceeding 1 km. This can be done by using an empirical law connecting the number of asteroids with their dimensions. Presuming that this regularity extends to asteroids with a diameter of 1 km, I. I. Putilin as early as 1939 computed the total mass of all asteroids, not smaller than the limit mentioned (under the condition that their mean density equals the mean density of the Earth), as close to one one-thousandth of the mass of the terrestrial sphere.

The best evaluation is made if consideration is given to the perturbation effect of the entire asteroid belt on the movement of Mars. In this method the mass of all asteroids, both discovered and undiscovered, is considered, including all fragmentary solid substances down to the smallest particles of dust inclusively.

The first evaluation by this method was made by Leverrier. Considering the deviation in the perihelion motion of the Martian orbit, Leverrier found that the total mass of all asteroids does not exceed 1/4 the mass of the Earth and, is probably close to 0.1 of the mass of the terrestrial sphere. Later, S. Newcomb, using this same methodology, found the mass of the asteroid belt to equal 1/6 the mass of the Earth. P. Hartser came to the same conclusion at the end of the last century.

Analyzing all of the computations mentioned in regard to this method, I. I. Putilin concluded that the total mass of the asteroid belt could not be less than 0.1 of the mass of the Earth. If we presume that the mean density of the asteroids equals the mean density of the terrestrial globe, the hypothetical planet Phaeton, the ancestor of the asteroid belt, must have had a diameter close to 5,900 km. With a mean density of 3.7 g/cm^3, the diameter of Phaeton would equal 6,880 km, which exceeds the diameter of Mars by 140 km. /46

Let us note that these, so to say, "gravitational" evaluations of the total mass of the asteroids provide understatements as results. There are other masses of asteroids left out of consideration, since they move outside the asteroid belt (e.g., the Trojans). On the other hand, there is no doubt that the original mass of the asteroid belt could have been substantially greater than it is now. The gradual fragmentation of asteroids generates fragments with extremely eccentric elliptical or even hyperbolic orbits which leave the asteroid belt forever, and fall onto the Sun or some other major planet or even abandon the solar system.

Perhaps there is no other region in the solar system where processes of destruction and degradation of matter would take place with such a uniform tendency as in the asteroid belt. There everything is breaking up, becoming smaller, "disintegrating" in near solar space, and there are no visible processes which would essentially replenish the decaying asteroid belt with matter.

The natural conclusion from what has been said is that Phaeton (if it actually existed) may have been a large planet of the Earth type, no smaller in size than Mars, or possibly even than Earth. We shall not yet turn to the problem of the reality of Phaeton, but will now direct the attention of the reader to other physical properties of the asteroids.

If all of the small planets were ideal spheres with a perfectly smooth surface, and thus had one and the same reflective capacity and color, even then the apparent brightness of the asteroids would not remain unchanged. The reason for this (besides a reduction in distance to the Sun and Earth) is found in the changes of phase of the asteroids.

The angle between a line from the center of the asteroid to the Sun and one to the observer is called the phase angle. The larger this angle is, the smaller is the apparent brightness of the small planet (other conditions being equal). However, the relationship between these magnitudes depends to a great degree on the nature of the surface structure of the small planet, on how it disperses the solar rays striking it. This means that a person studying the changes in /47 apparent brightness of an asteroid as a function of its phase can reach a few conclusions about the structure of its surface.

Leonhard Euler found that the illumination of any surface depends (in addition to the power of the light source and its distance from it) only upon the angle of incidence of the light illuminating the surface. If we designate the brightness of the spot which the observer sees with the letter B, the angle of incidence with the letter i, and the illumination of the given spot with the letter E_0, Euler's function is expressed by the simple equation:

$$B = E_0 k \cos i,$$

where k is some constant.

Let us designate the angle of diffuse reflection as e, the angle between a perpendicular to the surface of the body at the given spot and the ray coming from this spot to the observer. Then, according to the law proposed by Lambert

$$B = E_0 k \cos i \cos e.$$

There are still more complicated laws upon which we shall not dwell. Taking Euler's law and Lambert's law, it is not difficult to find the theoretical dependence of the apparent brightness of an asteriod from the phase angle. Comparing this with given observations, it is possible to conclude whether the surface of the given asteroid fits, for example, Lambert's law or, if it does not fit, what caused the deviations observed.

Many years observation has shown that theory differs from experiment. The changes in brightness recorded from the phase angle are far larger than those which theoretical equations predict. Roughly speaking, the apparent brightness of an asteroid has proven to be proportional to its phase angle. On a graph the reaction between the apparent stellar magnitude and the phase angle is illustrated by a straight line. The tangent of the angle of inclination of this straight line to the horizontal angle is called the phase coefficient.

The phase coefficients of different asteroids are essentially different. It follows from this that the surface structure of small planets is not uniform. On the other hand, the deviation between theory and observations has been caused by the fact that asteroid surfaces are not absolutely smooth (as is assumed in theory), but on the contrary are very uneven and rough with numerous elevations and depressions.

So far we have been speaking about changes in brightness generated essentially by two causes, a reduction in the distance of the asteroid to the Sun and /48 to the Earth. In these cases the brightness changes slowly and all of the changes can be predicted on general charts, even though qualitatively. The other matter, the short-term, rapid, sometimes irregular oscillations and brightness, is undoubtedly inherent in the majority (if not all) of the asteroids: vacillations whose cause is far from being understood in all cases.

The first of these was spotted as early as 1901 by the famous German astronomer, Oppolzer while observing the asteroid Eros. In the next quarter century 72 more small planets were discovered with similarly rapid oscillations in brightness. In 1935 S. K. Vsekhsvyatskiy and Yu. V. Filippov stated that at least 44% of the asteroids known to them change their apparent brightness rapidly. Vacillations in the brightness of small planets was later studied by many astronomers, particularly V. P. Tsesevich at the Odessa Observatory. In short, it may be possible to come to the conclusion that all of the small planets without exception change their brightness with relative rapidity. In those cases where the amplitude of oscillation is great enough, the oscillation in brightness can be recorded directly. In other cases, they can only be guessed at with the assumption that they are too subtle for existing instruments. However, let us repeat that the entire matter is evidently one of sensitivity of apparatus. At any rate, depending upon the refinement of photometers, the number of "variable" asteroids recorded will grow continually.

The rapid oscillations in the brightness of small planets can be classified into two types: periodic and irregular. In the first case (e.g., for the asteroids Eunomia, Niza, Antigone and others) there is a sharply developed definite period approaching 4 hours on the average. The amplitude here is not great and as a rule does not exceed $0^m.4$. Although a skilled observer can provide accuracy close to $0^m.1$ in visually evaluating the brightness of variable stars, photometric recording of asteroid brightness is naturally preferable.

However, systematic visual evaluation of the brightness of the small planets also has scientific value.

It is difficult to indicate any cause for these phenomena except the rotation of asteroids around some axis. In this case the apparent brightness can change as some part of the surface of the asteroid with a different albedo turns toward the observer, for the reason that the asteroid itself has an irregular, fragmentary shape.

It is an interesting fact that asteroids which noticeably change their /49 apparent brightness, remain unchanged in respect to color (within the limits of measuring exactness). This means that the main cause is not to be found in a difference in color and structure among separate parts of the asteroids, but rather in their irregular, fragmentary shape.

Imagine some gigantic lump "somersaulting" through space. Like the irregular shape of an asteroid, at certain times it will reflect streams of solar light of varied intensity toward the Earth. This is where the oscillations in brightness, noted by terrestrial observers, come from.

It is more difficult to explain the changes in brightness where no periodicity can be determined. Such, for example, is the case of the small planet Brutsiya, which changes its brightness very tangibly (up to $1^m.5$) from one opposition to another, now appearing more clearly and now more dimly. The asteroid Eros is no less enigmatic in its variability in brightness.

Perhaps no other small planet undergoes as thorough a change in brightness as does Eros. Although investigations have been going on for almost seven decades, there is a great deal which is still not clear today.

The curve of brightness of Eros is complicated. It includes a double periodicity with periods of 2 hours 51 minues and 2 hours 25 minutes, so that the entire period of brightness is 5 hours and 16 minutes. The amplitude does not remain constant, either, but changes in a rather complex fashion.

There has not been any lack of hypotheses. It has been suggested that Eros is a double planet, consisting of two adjacent cigar-shaped bodies. Other astronomers have attributed a pear-like shape to Eros. They have tried to explain the facts by saying that the albedo of various parts of Eros are essentially different. Finally, they have even assumed the existence on Eros of mountainous crystalline rocks with so-called quasispecular reflection. But all these devices have proved useless.

In 1931, at the time Eros approached the Earth, it appeared in the 27-inch refractor of the Johannesburg Observatory as rather elongated, reminiscent of the figure 8. Let us note that all the oscillations in brightness do not produce any changes in the color of Eros. This means that the oscillations in brightness of Eros can be partially explained by its irregular shape. Other causes are still waiting for investigation.

The color and hue of small planets are characterized, just like stars, by a color index which we have already mentioned. By this term we mean the difference between the stellar magnitude of an object, as it appears without change on negatives (photographic stellar magnitude), and the stellar magnitude of the same object under visual evaluation. As the human eye is more sensitive to yellow and green, and the photographic plate to blue and violet rays, the color index will naturally not be identical for objects of different colors. For example, for red stars photographic brightness is less than visual brightness, while for blue stars it is the opposite. White stars of spectral class A0 are recorded at the zero point, for them the color index is considered equal to 0. Then for blue stars the color index will be negative and for yellow, orange and red stars, positive. Speaking more concretely, blue stars have a mean color index close to $-0^m.33$, yellowish $+0^m.33$, yellow $+0^m.67$, orange $+1^m.12$ and red $+1^m.73$. /50

As early as 1911 Hertzsprung found that the color index of Ceres equals $1^m.05$. Since the asteroids reflect solar light, and the Sun is a yellow star with a color index of $+0^m.79$, obviously a small planet with a purely white surface would reflect the same color index. This means that a small planet with a larger color index will be yellow-orange or red.

The pioneer work of Hertzsprung was not confirmed later, and according to modern data the color index of Ceres equals $0^m.70$, i.e., it has almost a neutral (grey) color, as do the rest of the asteroids on the average. However, in individual cases a very significant deviation from the grey norm is found. Let us mention the asteroid Fortuna (color index $+0^m,02$) which possesses a bluish tint, the asteroid Pompeya (color index $1^m.15$) which is yellowish, like the Moon, and the asteroid Amherstiya (color index $+1^m.31$) which is rather reddish--orange. It is a remarkable fact that the mean color indices of the asteroids ($+1^m.03$) and of the meteorites[11] ($+1^m.08$) are almost equal, a fact independent of many other accentuated identities in the nature and origin of these celestial bodies.

Spectral observation of the small planets began about 100 years ago in 1874 when Vogel studied the spectrum of Vesta visually. The result obtained was unexpected, as in the spectrum were distinguished the radiation line of hydrogen H_β and two streaks with wavelengths of 577 and 518 millimicrons. Later, the /51
majority of researchers disputed this result, but not long ago N. A. Kozyrev again evidently observed an analogous spectrum on Vesta.

Naturally there cannot be any atmosphere on Vesta nor on the other asteroids; their mass is too small. But the possibility of sporadic emissions of gas, caused by solar heating and other factors, cannot be excluded. Let us add that Vesta is a unique asteroid in many respects. The violet end of Vesta's spectrum weakens periodically, possibly connected with its axial rotation and a non-heterogeneity in the structure of different parts. Some observers have recorded noticeable oscillations in the color index of Vesta, while others on the contrary affirm that it is constant. Analogous changes in spectrum have also been

[11]The color index of fresh chips are also investigated in meteorites.

observed in many other small planets. In general it should be noted that the majority of asteroids have very weak violet and ultraviolet areas of their spectra, and sometimes they simply do not exist. The reason for this phenomenon has not yet been explained.

In the 30's of the present century, Lyot, and other astronomers after him, undertook the study of the reflective power of small planets. They explained that in many cases in this regard the asteroids and Moon resemble one another; this means that the rocks, lying on their surfaces, are also similar. It should be stated, however, that in its reflective properties Vesta proved to be much more like chalk than like the lunar surface, still another mystery of asteroid No. 4.

Our information about the physical properties of asteroids is far from complete, although physical investigation of these asteroids began at almost the same time as the discovery of the first small planets. But up to recent times they have been carried on from one case to another, without any special scientific international program. For the most part this has been considered, and still is today, a problem of celestial mechanics. The success of the astronauts, however, will put the physical study of the small planets into the stream of currently important problems of astronomy.

SMALL BODIES IN THE SOLAR SYSTEM

Asteroids, comets, and even products of their destruction (meteorites, meteoric bodies and cosmic dust) are covered by the term small bodies of the solar system. This terminology is somewhat arbitrary: the well-known satellites of the planets, smaller in size than many asteroids, are still not included in /52 the group regarded as small bodies. Thus, for example, of the twelve satellites of Jupiter, 8 have diameters smaller than 160 km; of the nine satellites of Saturn, 4 are smaller in size than asteroids. Nereid, the second satellite of Neptune with a diameter around 300 km, could also be considered a small body. Phobos and Deimos, the satellites of Mars, are just crumbs.

However, small size is only one of the characteristics uniting the small bodies of the solar system. No less essential is a second mark, independent revolution around the Sun. In this connection, the smallest of the asteroids and the largest of the meteorites resemble each other very closely.

How far can the analogy, the similarity of all small bodies, be carried? Are they united merely because of their external features or are there facts which attest to a community of nature and origin?

We will try to answer these questions by first comparing asteroids and comets.

Comets are among the most amazing and at the same time the least studied celestial bodies. The unexpected appearance of comets, their complex form, their rapid changes and subsequent disappearance, all these phenomena have stimulated universal interest since antiquity and have demanded explanation.

Comets are colossal in size. Their tails stretch out for hundreds of millions of kilometers, and the diameter of the main part of comets often exceeds the diameter of the Sun and stars. But, in spite of this gigantic size, forcing comets to be considered the largest bodies in the solar system, the mass of a comet is insignificantly small. The basic amount of substance in a comet is concentrated in its solid portion called the nucleus. According to the latest data, cometary nuclei are glacial lumps of frozen gases with diameters no larger than a few kilometers, including numerous solid particles, which are hard to melt, as impurities (Figure 13). Cometary nuclei revolve around the Sun in extremely elongated elliptical orbits. When a comet approaches the Sun, its nucleus is heated and the frozen gases volatilize and form the head and tail of the comet. The solid particles found in the nucleus serve as material for the formation of powdery tails and meteoric showers.

The comets are the seat of complex phenomena caused mainly by the effect /53 of solar heat, light and corpuscular solar radiation.

Modern means of observation allow comets to be detected when their distance from the Sun is still quite large (2-3 AU). At such a distance from the Sun, a comet in the telescope looks like a small, round, nebulous spot with a large, bright, star-shaped concentration in the center, the nucleus. The haziness surrounding the nucleus is called the coma.

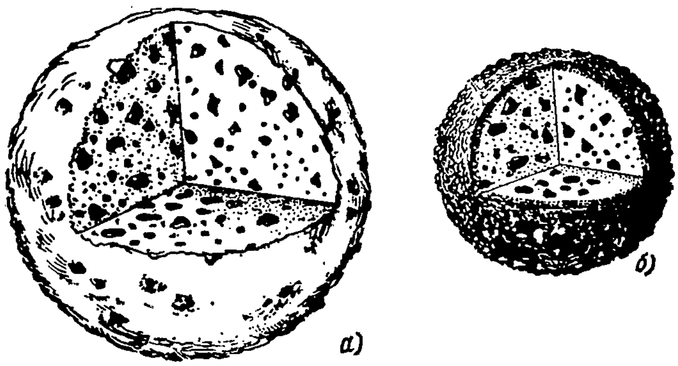

Figure 13. Cometary Nuclei.

As the comet approaches the Sun, bright and fan--shaped streaks, called discharges, begin to emerge from its nucleus in the direction of the Sun. The discharge phenomenon is accompanied by an increase in the general brightness of the comet. Increasing in size and expanding at the end, the discharges facing the Sun resemble shining fountains spurting from the cometary nucleus. This similarity is particularly accented when, as the comet approaches the Sun, streamers leave the ends of the discharges and curl away from the Sun.

Then the external edge of the discharge, facing the Sun, becomes more or less sharply outlined and forms a so-called shell. In its outlines, the shell is nearly a paraboloid with the cometary nucleus as its focal point. There are cases when not one, but a number of shells are observed, adjacent to one another and having their common focal point in the cometary nucleus.

The coma, nucleus discharges and shell form the head of the comet. As the /54 comet approaches the Sun, the streams from the discharge surround the nucleus on all sides and extend out in the direction opposing the Sun, thus forming one or several cometary tails. Some of the cometary tails are almost straight lines while others have a noticeable curve.

Very rarely, unusual tails are formed on comets. They look like cone-shaped projections pointing from the head of the comet in the direction of the Sun. Finally, it is possible to observe a shining ring around some comets with its common center in the cometary nucleus. These are called halos. It has been observed that the halos gradually increase in size but keep their concentricity around the nucleus and maintain their annular shape. Three basic types of tails have been demonstrated. Tails of type I are rectilinear and stretch out along the entire radius vector[12] of the cometary nucleus in the direction opposite the Sun (Figure 14).

Figure 14. Great January Comet of 1910 Showing Two Typical Cometary Shapes.

In old drawings of comets, tails of type II are usually seen in the shape of curved brushes or sabers. Here is seen their characteristic feature; as a rule they are wider than tails of type I and curve in a direction opposite the movement of the comet. Tilted even more in this same direction are the tails of type III, differing from tails of type II because they look like bright bands of light in straight lines stretching out from the cometary nucleus. Finally, observations are sometimes made of abnormal tails, cone shaped projections from the cometary head pointed toward the Sun.

The physical nature of the cometary tails of different types is varied. Tails of type I are gaseous and composed exclusively of ions (CO^+, N_2^+, CO_2^+ and others). In tails of type II are found small bits of dust (their diameters are on the order of 10^{-5} cm) liberated from the cometary nucleus. In addition, it is possible for tails of type II to

[12]The straight line segment connecting the Sun and the nucleus is called the radius vector of a cometary nucleus.

include some neutral molecules and the products of their dissociation. Solid particles forming unusual tails are so large that the light pressure from the Sun's rays is practically unable to exert any influence upon them.

As far as the cometary heads are concerned, they include both dust (in the central portion near the nucleus) and neutral gaseous molecules (C_2, CH, CN).

The physical science of comets was begun in the last century already but only in the last ten to fifteen years has this branch of astrophysics reached the unusual flurry of progress which is the general characteristic of modern science. Only now has it become obvious how complicated the physical processes in comets are and how naive were the claims of those cometary researchers who thought in the past that it was possible to explain cometary phenomena by purely mechanical causes. /56

Any comet can be considered as a small body with a constantly renewed atmosphere. As mentioned already, the grandiose sizes of the heads and tails of comets still do not give us the right to consider comets as gigantic celestial bodies, since almost the entire mass of a comet is concentrated in its very compact nucleus. As far as the heads and tails of comets are concerned, their mean density is billions of times smaller than the density of air in our rooms, a fact attested to by the well-known descriptive name for comets ("nothing visible").

Cometary nuclei have come close to the Earth and other major planets more than once, but these passages have not produced any changes in the latter. There have even been cases (e.g., 1910) where the nucleus of a comet passed between the Sun and the Earth. However, even such close encounters did not produce the desired results, no traces of the cometary nucleus could be observed against the background of the solar disk. These facts attest to the extremely small mass of a cometary nucleus.

The telescope is able to distinguish star-shaped concentrations, so-called photometric nuclei, in the center of the cometary head. But even this is not the real solid nucleus which serves, so to speak, as the "base" of the comet. The greater the telescopic enlargement used, the smaller is the photometric nucleus, and this is a reliable sign that in a given case we see a gaseous mass with a spherical extension of its density surrounding the solid nucleus.

In the history of cometary astronomy there are evidently only two cases where the real nucleus of the comet has been successfully glimpsed. This happened in 1927 and in 1930 when comets 1927-VII and 1930-VI approached our planet at a distance of several million kilometers. The famous French astronomer, Balder at the Meudon Observatory noted star-shaped objects in cometary heads which were not reduced when the ocular power was increased. In Balder's judgment, the diameters of the cometary nuclei (with an albedo of 0.1) in both cases approached 400 m, a result not very different from reality. /57

How can the structure of a cometary nucleus be represented? What is this cluster of tiny particles, a monolith of the type of a gigantic meteor or something else?

In 1950, the Kazan astronomer, A. D. Dubyago showed that in the nucleus made of chunks of material separate chunks will collide with each other every so many minutes, thus breaking up and eliminating themselves. As these collisions produce a liberation of heat, which inevitably is lost to the nucleus, the total mechanical energy of the nucleus will gradually be reduced. As a result, after a short period of time the activity of the separate chunks in the nucleus is curtailed and the mass congeals into one compact body.

However, this again causes difficulty. It is impossible to consider the cometary nucleus as a monolithic body of relatively small dimensions, since in this case we cannot understand how a considerable amount of gas can be liberated from such a small square surface of such a nucleus as it approaches the Sun.

A way out of this difficulty is found at the present time in the "glacial" model of a cometary nucleus, first suggested way back in 1947 by S. K. Vsekhsvyatskiy. According to modern opinion the fundamental mass of the cometary nucleus is composed of "ice" of various gases, methane, ammonia, carbon dioxide and others. With these there is also found some regular aqueous ice. All of these "ices" are not pure; numerous solid particles of a metallic or stony character, hard to melt, are mixed with them. When such a monolithic "glacial" nucleus approaches the Sun, the solidified gases evaporate, passing the liquid stage (volatilizing), and the solid particles occurring in them as impurities settle on the surface of the nucleus and form a more or less thick layer of solid dust. The poor heat conduction of this layer prevents the "glacial" nucleus from vaporizing too quickly and guarantees the comet a fairly long existence.

When we speak of cometary "ices", we may be making use of an inaccurate representation, namely that these pieces of ice are similar in density, let us say, to the well known greenish chunks of river ice which we know so well. In actual fact this is not the case. Cometary nuclei, constantly disintegrating, form meteor showers. Particles of these showers and sporadic meteoric bodies, which have long since lost contact with their meteoric ancestors, collide with the Earth and rush along the horizon as meteors. And if at such moments the meteor /58
is caught on a photographic plate, its spectrum studied, its other physical properties studied, and especially, if it is clear how the meteoric body slowed up in the atmosphere, then it is possible to determine the mean density of this particle of the cometary nucleus. According to many quite reliable data, this density approaches 0.1 g/cm^3. In other words, the cometary "ices" in their density are more similar to very light snow than to anything like the density of ice.

In comparing asteroids with comets we shall not go into detail about the physical processes which take place in the tails and heads of comets. Let us only mention that the gradually renewed atmosphere of a comet exists mainly under the influence of solar radiation, electromagnetic and corpuscular. The role of the former is not only to heat the cometary nucleus and, so to speak, stimulate all of the active processes observed in comets. The pressure of the solar rays is a repulsive force which compels cometary tails (except abnormal ones) to move in a direction opposite the Sun.

Usually, however, light pressure proves to be insufficient for explaining all of the gigantic repulsive acceleration which is typical of the particles of tails of type I. Here, another factor, the corpuscular radiation of the Sun, plays the major role.

The stream of corpuscles (mainly protons) given off by the Sun carries along with it a so-called "icebox" magnetic field. Although its intensity is extremely small (on the order of 10^{-4}-10^{-5} oersteds), the interaction of this field with the plasma of the cometary head and its tails when they meet proves to be quite considerable. As researchers of the last few years have pointed out, such interaction can explain, not only the shape of tails of type I and the repulsive acceleration observed in them, but also many other cometary phenomena. Two or three decades ago, when the physical nature of comets was poorly known, hypotheses were expressed about the close relationship (if not identity) between comets and asteroids. In this matter reference was made to the old observations of W. Herschel and Schroeter, as though they had seen Ceres and Pallas surrounded by some kind of nebulous shell. Mention was also made of the much more recent (1928) observations of Komas-Sol, who was convinced that he had successfully ascertained a nebulous shell on the asteroids Okeana and El'za. On the other hand, mention was made of the unique comet of Schwassmann-Wachmann, rotating /59 around the Sun in a slightly elongated ellipse between the orbits of Jupiter and Saturn. Some of these comets (e.g., 1913-III) had a scarcely distinguishable coma.

Today all of these deliberations seem inconclusive. There are absolutely no constant gaseous shells around asteroids. On the other hand, the atmosphere of a comet is an extremely characteristic and always observed detail of these celestial bodies. The nucleus of a comet, of the consistency of light snow, is formed of tiny solid particles. All of the small planets are monoliths, reminescent in this regard of planetary satellites or meteorites.

Only a few cometary orbits resemble the orbits of asteroids to a slight extent (e.g., the orbit of the comet Oterma). But on the whole in all of these combinations of elements of cometary and asteroidal orbits there is almost nothing in common. Thus, for example, the semi-major axis of the orbits of almost all asteroids is inclined within limits of 2.2 to 3.6 AU. Comets are different: the mean index of the semiaxis of the orbit of short-period comets is equal to 5.9 AU. As far as long-period comets are concerned (and these are the majority), their semiaxes exceed the semiaxes of asteroidal orbits by tens and hundreds of times.

There is just as much difference in the spread of their eccentricities. About 98% of the asteroids have orbits with eccentricities not exceeding 0.33. However, even short-period comets (with some exceptions) have eccentricities greater than 0.4. To this we can add the fact that in the distribution of their perihelion longitudes, their nodes and their inclinations, comets rather "replenish" the asteroids than form any similarity to them.

In celestial mechanics attention is given to a magnitude called Jacobian functions[13]. It can be proven that if several celestial bodies have a common origin, their Jacobian functions should be very close to each other. This is explained by the fact that, no matter what perturbations their original orbits have been subjected to, their Jacobian functions remain almost unchanged.

The physical concept of Jacobian functions is quite simple. Imagine an asteroid traveling along under the influence of attraction by the Sun and by /60 Jupiter (the attraction of the other bodies is negligible). Here it is presumed that the Sun and Jupiter rotate around the common center of their masses in circular orbits. If the motion of the asteroid is viewed in relation to Jupiter and the Sun, the full energy of the asteroid will be the Jacobian function in such relative movement.

These theoretical conclusions have successively withstood expert verification a number of times. Thus, let us say, in asteroids of one and the same family the Jacobian functions are almost identical. Whether there is a similarity in the Jacobian functions of comets and asteroids is a question upon whose solution depends a final answer concerning the relationship of these celestial bodies.

Jacobian functions for asteroids and comets have been determined by many researchers, but conclusive results had already been achieved by 1939 by A. N. Chibisov (for asteroids) and by T. V. Vodop'yanova (for comets). The Jacobian functions h turned out to be restricted to comparatively narrow limits for asteroids:

$$-805\cdot 10^{-7} > h > -1075\cdot 10^{-7}.$$

[13]For more details see I. I. Putilin, [1].

Let us note that if h is inspected for separate asteroid families, it is almost one and the same within the limits of one family. For comets h has been found lying within very large limits:

$$-859 \cdot 10^{-7} < h < +178 \cdot 10^{-7}.$$

In the post-war years analogous results were obtained by G. F. Sultanov.

It is evident that h is different for comets and asteroids. This last argument only complements what has been said above about the dissimilarity between comets and asteroids in all physical properties. Celestial mechanics only confirms this conclusion that there is nothing in common between comets and asteroids. These small bodies of the solar systems have different physical natures and different origins.

Our modern concept is that our planetary system is surrounded on all sides by a gigantic cloud made up of a large number of chunks of "impure" (i.e., having solid inclusions) ice. Each such glacial lump is a potential cometary nucleus. Flying near the Sun it is heated, acquires a gaseous head and tails, or in other words turns into a typical comet. But such cases are not frequent and the majority of potential cometary nuclei making up this "cloud of Oort", has an /61
elliptical orbit with semiaxes of from 50 to 150,000 AU. Along with this their orbital elongations and their inclinations to the plane of the terrestrial orbit are extremely different. As the well-known Leningrad astronomer G. A. Chebotarev demonstrated in 1964, under the influence of perturbations on the part of the core of the Galaxy and individual near stars, lumps from Oort's cloud can either leave the solar system forever in a hyperbolic orbit or conversely approach the Sun and become regular short-period comets. This latter variation is theoretically supported in the works of the theoretician from Riga, K. A. Schteyns.

Direct observations are actually available to us in the fact that many of the long-period comets come into the vicinity of the Sun from interstellar space from distances nearly half-way between the Sun and Alpha Centauri.

Entering a short-period orbit, a potential cometary nucleus acquires a coma, and then a tail, and in this way begins its journey of gradual destruction.

In every passage close to the Sun a comet loses matter from its nucleus. An encounter of this nucleus with a random meteorite can convert the nucleus into an aggregation of small fragments; is this not what happened with Biela's famous comet? However, for some comets with very loose nuclei and perihelia near the Sun, the solar globe itself may simply prove to be destructive. Somehow the brightness of a comet, as was established some decades ago by the famous Soviet comet investigator S. K. Vsekhsvyatskiy, is reduced with every revolution around the Sun and only 150-200 revolutions are necessary for the comet to completely disintegrate. However, these conclusions are not indisputable. The researcher from Leningrad, G. A. Chebotarev, maintains that the ages of comets may be hundreds and thousands of times greater.

It is possible that the replacement source for comets is not only the numerous glacial lumps which are found in the periphery of the solar system. As S. K. Vsekhsvyatskiy suggests, explosive and eruptive processes on large planets and on their satellites may lead to the ejection of ice covered lumps into interplanetary space. Under the influence of solar radiation each of these lumps has every opportunity of becoming a comet.

There are no universally recognized hypotheses for the origin of comets. However, it is clear that whatever is decided from the discussions now going on /62 about this problem, we can in no wise explain the origin of comets as we have explained the formation of the asteroid belt in the solar system.

Now we shall turn to meteorites and try to show that there is more than a similarity between asteroids and meteorites. In essence asteroids and meteorites are bodies of one nature. We call meteorites those asteroids which, occupying a very elongated elliptical orbit, collide with our Earth and as a result drop to the terrestrial surface.

Unfortunately there are few reliably determined meteorite orbits. No one knows ahead of time where and when a meteorite will fall. The fall of a meteorite takes place in a completely unexpected manner, its flight in the atmosphere lasts only a few seconds and only occasionally, in a purely random manner, are there reliable sightings of the flight of a meteorite between two or more points.

Under such conditions simple computations provide all the elements of the initial orbit of the celestial body colliding with the Earth.

Such an exceptionally fortunate situation occurred once on 12 February 1947, when a large meteorite fell in the Far East in the region of the Sikhote--Alin range. This flight was witnessed by hundreds of observers, both on the surface of the Earth and from an airplane, and the artist Medvedev from the city of Iman was even able to portray this unexpected "detail" on a landscape drawn by him.

On entry into the terrestrial atmosphere the mass of the Sikhote-Alin meteorite consisted roughly of a thousand tons. Braked in the atmosphere, the meteorite exploded into a large number of fragments which fell upon the Earth, thus causing cone-shaped depressions, so-called impact meteorite craters. Among the fragments sent to Moscow are some extremely tiny ones, weighing part of a gram, and chunks weighing almost two tons.

The orbit of this space visitor, computed by N. B. Divari, proved to be extremely noteworthy. Its semi-major axis equalled 2.16 AU, and its eccentricity was 0.54. Perihelion was located close to the terrestrial orbit, orbital inclination amounted to 9.4° and the distance from the Sun at aphelion was 3.3 AU (Figure 15). In short, the fragments, called the Sikhote-Alin meteorite by us, came to us from the asteroid belt, from the very densest part of the asteroid ring. This case is far from being singular.

In the Spring of 1959 Czechoslovak astronomers at several stations mounted /63 special automatic cameras. And it was necessary for this to be done; on 7 April 1959 not a simple meteorite, but a swarm of meteorites, a real meteorite shower, flew down onto Czechoslovakia to receive the name Pshibram. It is remarkable that the flight of meteorites was photographed at the same time from two points 40 km apart. Essentially the same thing had happened in 1947. A fragile lump from space could not withstand the resistance of the atmosphere and without reaching the earth exploded into a large number of fragments forming a meteorite shower. The original orbit of the meteorite was established much more reliably than was done for the Sikhote-Alin meteorite.

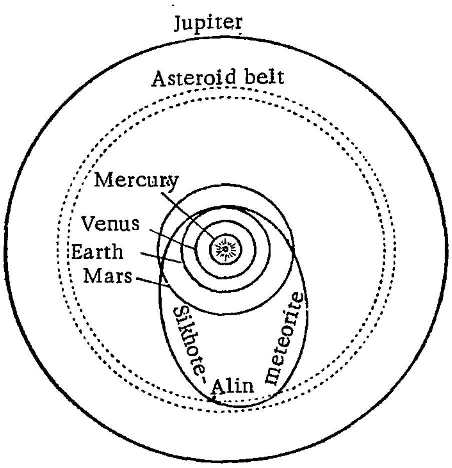

Figure 15. Orbit of the Sikhote-Alin Meteorite.

Again it was possible to confirm that the visitor honoring us came from the asteroid belt, but this time the aphelion of the orbit of the Pshibram meteorite was located closer to the orbit of Jupiter. If this collision with the Earth had not been fatal for the meteorite, it would have gone almost as close to the Sun as Venus.

Compare the orbits of the Sikhote--Alin meteorite and Pshibram meteorites with the orbits of the asteroid Icarus. They are extremely uniform, and this is not a random similarity, since it is supported by other data.

The Sikhote-Alin meteorite was a very small body; upon its entry into the terrestrial atmosphere its diameter did not exceed a few meters. But it managed to strike the Earth, and this happens often with far larger meteorites.

If the mass of the meteorite is considered to be several thousands of tons /64 or even more, the terrestrial atmosphere is not able to brake the body from space. With its original velocity almost unchecked, it digs into the surface of the Earth, at which time the kinetic energy of the meteorite turns into the energy of a massive explosion. The term "explosion" here is not a merely descriptive phenomenon, but an absolutely exact description of its physical characteristics. When it collides with the Earth the crystal lattice of the meteorite instantly breaks apart and the meteorite essentially becomes, not a solid body, but an extremely condensed gas. The gas expands precipitously and liberates energy. It is estimated that, if the velocity of the shock is equal to 4 km/sec, the meteorite explodes with as much power as an equal amount of TNT. With an increase in velocity, the liberation of energy increases rapidly. That is why encounters between gigantic meteorites and the Earth leave so-called "scars" on the surface of the Earth, the craters of exploded meteorites. In form they suggest the cones caused by exploding bombs or mines, and inside them there are very little traces or none at all of meteorite fragments (the mass of the meteorite practically volatilizes upon explosion), but the dimensions of such craters may be extremely impressive. In this way theory makes it possible to closely estimate the sizes of meteorites which form such explosive craters.

Until recent times the large meteorite crater in Arizona was considered the largest. It has a diameter of 1.2 km, it goes down as deep as 175 meters, and against the uniform background of the Arizona desert this scar from space is extremely noticeable. It can be calculated that about 25,000 years ago at this spot a meteorite, with a diameter of about 25 m and a weight on the order of 60 to 70,000 tons, plowed into the Earth.

Recently meteorite craters of much greater sizes have become known. In South America, first by airplane and later on the ground, gigantic meteorite craters with diameters up to 32 km were observed. The so-called ring of Vredefort, with a diameter of 50 km, has been known in South Africa for a long time. It can be calculated that this scar on the face of the Earth is the result of the fall of a meteorite having a diameter around 1.5 km.

But even such an immense lump does not match the size of Icarus, Hermes and /65 the large number of typical asteroids known to us. On the other hand, a meteorite crater with a diameter around 250 km was recently sighted in Antarctica under a layer of ice. Some researchers adduce convincing arguments to support the fact that the bulge of Hudson's Bay is only part of the embankment from a crater caused long ago by an exploding meteorite with a diameter of 440 km. But then it turns out that the Earth preserves the traces of encounters with asteroids possessing diameters in tens of kilometers!

This suggests the natural conclusion that both in respect to orbits and in respect to size meteorites and the smallest of the known asteroids resemble each other.

The few physical characteristics of asteroids which can be determined immediately from astronomical observations and, on the other hand, data from the laboratory study of meteorites again indicate close relationship between these celestial bodies.

The oscillation and brightness of asteroids indicate their imperfect, fragmentary shape. But this is the same shape which meteorites have. Under laboratory conditions it is possible to determine the color index for various meteorites, for the stellar magnitude is a standard of brightness measured by laboratory equipment.

The color indices of meteorite are within the limits of $+0.76^m$ to $+1^m.39$, amounting to $+1.08^m$ on the average. For asteroids the limits of the color index are $+0.79^m$ and $+1.37^m$, with a mean value of $+1.00^m$, i.e., practically the same as in meteorites.

Let us say a few words about the dissociation products of comets and asteroids. They are diverse, just as these small bodies themselves are diverse. Splitting and breaking apart, cometary nuclei normally generate loose, snow-like meteor bodies. Judging from appearances, the process of asteroid shrinkage (as a result of mutual collisions) leads to the formation of tiny solid space dust. Up-to-date elements of space apparatus record particles of dust with a weight of only 10^{-13} grams, but even this is evidently not the limit of fragmentation of asteroidal material.

It is natural to think that the tiniest fragments from asteroids are much more compact than typical meteor bodies, in this regard approaching iron and stone meteorites. Academician V. G. Fesenkov studied the process of gradual decay, "disaggregation" of asteroids from a quantitative point of view[14]. As a /66
result of calculations carried out by him, he came to the conclusion that "no matter in what way fractionization of the asteroids occurred, no matter at what speed ejection occurred, a considerable part of the cosmic dust must be concentrated in the asteroid belt."

Thus the cosmic dust is concentrated within the asteroid belt and in the close vicinity of the asteroid ring. But a fine dusty veil evidently embraces the entire planetary system, forming the main constituent of the so-called

[14]See Fesenkov, [4].

zodiacal light[15]. Local aggregations in the vicinity of the major planets and their satellites do not change the general picture. Is not the cloud of dust envelopping the planetary system a graphic indication of the gradual disintegration of the asteroid ring which is to end in its complete disappearance?

ASTEROIDS IN THE LABORATORY

The reflections in the previous section fully justify the title of this section. In actuality, if a meteorite should fall into the laboratory, there would be every reason to consider it an independent asteroid or, at worst, a fragment from a small planet.

Such events do not happen often. Most meteorites fall into the ocean or onto immense, sparsely populated stretches of the Earth and in this way evade the hands of investigators. If we believe the data obtained with the help of space devices, many thousand tons of fragmentary solid cosmic material fall onto the Earth every day. This is usually cosmic dust, small to very small, the "remains" of asteroids and parts of comets. A portion of these "remains", on the order of tons or tens of tons, is attributed to meteorites. But only a very few of them are identified and subjected to laboratory investigation.

Meteorites from 1800 falls are preserved in many museums of the world. The portion of them in Soviet collections includes meteorites /67
(individual specimens and fragments) from 134 falls. Let us note that in falling or in striking the Earth some meteorites are broken up into a large number of fragments. Thus, for example, around 3,000 fragments were collected from the meteorite shower at Pultusk in 1868. For this reason the number of meteorite specimens is far greater than the number of falls. However, the total mass of all meteorites collected and studied is very small.

Because of the difficulties of moving them and for other reasons, some of the meteorites found continue to lie on the surface of the Earth and attract curious tourists. Such, for example, is the Hoba meteorite (60 tons!) found

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[15]Electrons which reflect solar light are also found in the zodiacal light.

in Southwest Africa or, let us say, the Bacubirito meteorite (weight 27 tons) found in Mexico. The largest meteorite found in a museum is the famous Greenland meteorite preserved in the New York Planetarium. It is just short of weighing 34 tons!

A meteorite colliding with our planet is first affected, not counting the gravity of the Earth, by the resistance of the terrestrial atmosphere. The flight always takes place at supersonic velocity and for this reason a very hot and bright shock wave is generated in front of the flying meteorite. Under collision with molecules in the air the surface of the meteorite melts and volatilizes, and thus the atmosphere gradually wears away the meteorite, layer by layer. If it is not tough enough, this inevitably causes the meteorite to disintegrate into small fragments. The atmosphere "erodes" tough celestial stones and gives them a streamlined appearance.

The literature about meteorites is quite extensive. For a beginning we recommend to those who are interested in detail two reliable monographs which incidentally include a list of other books on the same subject [5, 6]. Here, however, we shall limit ourselves to a brief characterization of the physical and chemical properties of meteorites.

By composition and structure meteorites are divided into three basic groups: irons (siderites), stones (aerolites), and stony-irons (mesosiderites).

Iron meteorites (Figure 16) present a fusion of iron with nickel, the latter being present to a noticeable degree (from 5 to 30%). In contradistinction to terrestrial iron, meteorite iron is hammered easily when cold. It pos- /68 sesses a peculiar crystalline structure which shows up on some iron meteorites if the surface is polished and etched with a weak acid solution. Then figures are distinguished which somewhat resemble the frost patterns on windows. These so-called Widmanstaetten figures are characteristic of octahedrites, a special variety of iron meteorites. In other varieties, hexahedrites, under the same conditions we find a network of very thin straight lines called Neumann lines. While the Widmanstaetten figures attest to the fact that formation took place under great pressure and temperature, i.e., in the depths of a fairly large planet, Neumann lines are evidently the traces of explosive shock waves made when the planet exploded. However, in the opinion of a number of researchers, Neumann lines could have been formed at the time of condensation of the original body if drops in temperature within it were very great. In other words, it is possible that Neumann lines came into being as the result of "temperature" stresses. Iron meteorites also include ataxites which do not have any conspicuous crystalline structure of their own.

Figure 16. Fragment of the Sikhote--Alin Meteorite.

Stone meteorites are composed predominantly of silicates, i.e., siliceous compounds with a sulphur grey color at fracture; nickel /69 iron also appears here in the form of separate shiny grains scattered throughout the stone mass. Other grains of a golden bronze color can be distinguished; this is troilite, a compound of iron with sulphur. Almost black stone meteorites, or conversely very bright ones, are rarely found.

Two subclasses of stone meteorites, chondrites and achondrites, are divided mainly by the fact that the first have chondri, small round vitreous formations ranging from microscopic bits to the size of peas (Figure 17). Most chondri have diameters on the order of 1 mm. They are usually distributed throughout the mass of the meteorite, so they are quite easily noticed on a freshly broken surface.

Around 90% of all stone meteorites can be classified as chondrites. Chondri are not found in achondrites, which sometimes have a rubbly structure. They do not have any (or almost no) nickel iron.

A special group of carbonaceous chondrites, rich in organic matter, must be singled out from the stone meteorites. They are very brittle, do not persist well and are treasured as great rareties: only a score of carbonaceous chondrites have been collected in the whole world. When crushed between the /70 fingers, the substance of carbonaceous chondrites gives off the characteristic odor of oil, a sign of the presence of bituminous compounds in the meteorite.

Figure 17. Chondrite of the Staroye Boriskino Meteorite (Microscopic View).

Stony-iron meteorites, as the very name indicates, contain features of both previous classes. They contain approximately half nickel iron and half silicates. Some of the meteorites of this class (so-called pallasites) are reminiscent of sponge iron with the cavities filled with mineral olivine.

Naturally, there are no sharp limits between the various classes of meteorites, but rather an even, gradual transition.

Chemical study of meteorites, as was to be expected, has revealed only the chemical elements which are also known upon Earth, one of the graphic illustrations of the material unity of the universe. Thus, no peculiarity of meteorites is found in the quality of chemical composition, but rather in the quantitative relationships of various elements, in their mineralogical structure, and in some physical peculiarities not typical of terrestrial bodies.

Most of the time such chemical elements as iron, nickel, sulphur, magnesium, silicon, aluminum, and calcium are found in meteorites. Oxygen is also plentiful, but is always found in some kind of chemical compound. Most characteristic of the latter for meteorites are SiO_2, Al_2O_3, and Fe_2O_3. Let us point out that such radioactive elements as uranium, helium, potassium, thorium, etc., have been found in meteorites. They make it possible to determine the age of meteorites, a very complex problem to which we shall return.

Basically, minerals found in meteorites are also found on Earth. Such are, for example, olivine $(MgFe)_2SiO_4$, magnetite (Fe_3O_4), chromite $(FeCr_2O_4)$, etc. Chlorite, an aqueous silicate often found in mountainous rocks on Earth, should be particularly mentioned. It is also found in meteorites; in 1949 L. G. Kvasha noticed bound (so-called constitutional) water for the first time in the chlorite of the Staroye Boriskino meteorite. It is curious that in this case water made up almost 9% of the total mass of the meteorite. Constitutional water was later found in other meteorites, too, and in carbonaceous chondrites its proportions sometimes reached 20% of the total mass.

Some minerals are indigenous to meteorites alone. These include, for example, schreibersite and iron phosphide $(FeNi)_3P$, found in the shape of round lumps in troilite. In a fresh condition, schreibersite reminds one of the color of tin. /71

The troilite mentioned above (a variety of FeS pyrrhotine) is also a frequent "meteorite" mineral unknown under Earthly conditions. There are a number of similar minerals and it is natural that any hypothesis about the origin of meteorites must find an explanation for these peculiarities.

Let us direct the reader's attention to several minerals whose existence in meteorites may illustrate the particular origin of these space bodies.

Diamonds (naturally in very small quantity) were first observed in meteorites as early as 1888 by the Russian researchers M. Yerofeyev and P. Lachinov. Later they were found in many meteorites, both stones and irons. Until recently it was thought that diamonds could be formed only in the central regions of the major planets under conditions of high pressure. However, it has become clear that not only static and gravitational pressure, but also high pressure caused by various shocks, can sometimes transform regular graphite into diamonds. Thus it has become uncertain whether meteorite diamonds originated in the depths of a major ancestoral planet or whether they were formed during collisions of meteorites with one another.

Quartz was first found in 1861 in insoluble sedimentation from many iron meteorites. At first the discovery of precipitated rock in meteorites aroused doubts. However, impregnations of quartz were found later in a series of iron meteorites and now there is no reason to deny their origin in space.

Copper occurs in many meteorites, both stones and irons, usually in the form of very small grains. There are reports of falls of copper meteorites both in the 17th century and in the present period. The reliability of these reports is questioned, but as we shall show below, without sufficient reason.

Sulphur has been extracted from some carbonaceous chondrites. Finally, as early as 1834, Berzilius [sic], and other researchers later, noticed a significant amount (up to 10%) of salts dissolved in water, mainly magnesium sulfates, in carbonaceous chondrites.

All of the minerals listed are particularly interesting because they support /72
the old hypothesis of Olbers about the major planet ancestor becoming the source of the meteorite [sic] belt when it disintegrated.

The physical properties of meteorites have been given their due attention only in recent times. In regard to their specific gravity, meteorites form a natural sequence from the heaviest iron meteorites (with a mean specific gravity of 7.72 g/cm^3) to the lightest stones (mean specific gravity 3.54 g/cm^3). The stony-iron meteorites find themselves in the middle (mean specific gravity about 5 g/cm^3). As already mentioned, meteorites are quite close to asteroids in their optical properties. Of the other physical properties, the most interesting is the residual magnetism reliably observed in very many meteorites. We shall show below that this fact, also, obviously confirms Olbers' hypothesis. But perhaps the most weighty argument for the reality of Phaeton, an earthlike planet and the ancestor of the asteroid belt, is the complex organic compounds and the possible traces of life which are found in many meteorites.

In 1806, at the very height of the Napoleonic Wars, an unusual meteorite fell near the French village of Aigle. This was only three years after the French "acceptance" of meteorites by the Paris Academy of Sciences. Prejudice against "celestial stones" was still quite strong and some of the fragments of the Aigle meteorite were simply lost, and after 28 years only one of them found its way to the laboratory of the famous Swedish chemist Jacob Berzelius. At first the scientist thought there had been a mistake, as the Aigle meteorite was not a stone, nor an iron, nor a stony-iron. The fusion crust, however, testified to the cosmic origin of the unusual stone from a very unusual source and from a type of meteorite still unknown, carbonaceous chondrites.

The Aigle meteorite possessed an organic[16] mass, soluble in water. When heated, its particles turned brown and formed a mass of coal, a clear sign of the presence of high molecular carbonaceous compounds. Although the similarity to terrestrial materials of this type was obvious, Berzelius wisely declared that this fact "is not yet a sign of the existence of organisms in the original /73 source."

The work of Berzelius marked the beginning of the organic study of meteorites. Unfortunately, material available for examination was very rare up to this time. Carbonaceous chondrites are excessively friable and can easily be pulverized with the fingers (and at this time, we repeat, they give off the characteristic odor of oil, the smell of bituminous compounds). Generally rare among meteorites, carbonaceous chondrites are easily destroyed during their flight in the terrestrial atmosphere, and if they hit the surface of the Earth, they usually disappear without a trace as they mingle with the terrestrial rocks. Therefore, it is not surprising that in the whole world there have only been a score of carbonaceous chondrites found and preserved (three of them in the Soviet Union), and that each of them is more valuable to science than gold.

Four years after the work of Berzelius was published, another carbonaceous chondrite fell in South Africa in 1838 and was then investigated by the famous German chemist Friedrich Wohler, the same Wohler who succeeded in synthesizing urea some years latter.

From the meteorite Wohler extracted a petroleum-forming oily substance "with a strong bituminous odor" and, in contradistinction to Berzelius, came to the conclusion that such materials could only be formed by living organisms "if we rely on the current level of knowledge."

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[16]Material containing carbonaceous compounds is called organic.

Again in France, in 1864, a meteorite shower made up of carbonaceous chondrites fell near the village of Orgueil, an event which is exceptional in he the history of astronomy.

Let us point out that the amount of organic material extracted from carbonaceous chondrites is not very large, roughly about 1%. But even this is enough for very important conclusions.

The French chemist Clets insisted strongly that the insoluble black material of the Orgueil meteorite represented organic compounds and not graphite nor amorphous carbon. The similarity of these organic compounds with similar substances found in peat and brown coal amazed him. In a lecture delivered at the Paris Academy of Sciences Clets maintained that organic materials in meteorites "can evidently indicate the presence of organic material on celestial bodies."

From this time on, for almost a hundred years the science of organic studies in meteorites was carried on randomly from case to case without any /74 essential general conclusions. Among these scarce works must be mentioned research on the meteorite Migei, carried out in 1889 by Yu. I. Simashko. The Russian scientist likewise noticed organic substances of a bituminous type in this carbonaceous chondrite.

It must not be thought that all organic materials are necessarily connected with life or, even more, belong to living beings. Astronomers are aware of many very simple organic compounds which have absolutely no direct connection with life. Let us mention as such the molecules CH and CN, observed in interstellar space and in the atmospheres of cold stars. Such organic substances as C_2, CO and others have been found in the heads and tails of comets. The volumes of ammonia and methane characteristic of the atmospheres of the lifeless giant planets, Jupiter, Saturn, Uranus and Neptune, are well known.

In addition to this, there is obviously a constant synthesis of extremely complex organic compounds under space conditions, including amino acids. In this matter we are particularly convinced by the recent inquisitive experiments of the American researcher P. Berger. With the help of elementary particle accelerators he bombarded a mixture of methane, ammonia and water, chilled to -230°C, with protons. After a few minutes the scientist noted in this glacial mixture such complex organic compounds as urea, acetamide and acetone.

In these tests Berger essentially modeled the conditions of interplanetary space. The stream of protons imitated the primary cosmic rays, and the mixture of methane-ammonia and regular ices was essentially a typical model of the cometary nucleus.

Another well-known American biochemist, M. Calvin, bombarded a mixture of hydrogen, methane, ammonia and water vapor with a stream of rapid electrons. In these experiments he obtained adenine, the basis for the structure of nucleic acid without which there can be no thought of protein forms of life. But did not such processes occur in the primeval atmosphere of Earth and of some other planets?

The impression is left that out of inorganic substances in an inorganic way high molecular protein compounds, "semifinished products" making future /75 life possible (but definitely not products of the decay of any living organism) are formed in space.

Thus, the mere presence of organic substances in meteorites cannot be regarded as evidence of life on celestial bodies. These substances could also have come into being in an abiogenic manner, without any direct connection with life. In order to prove the opposite other much stronger arguments are needed.

Discussion in the modern science of meteorites does bear upon this matter. The controversy is not ended, but the results obtained so far lend great interest to the subject of this book.

By 1951-1952 the English biochemist, Muller had extracted bituminous compounds from the carbonaceous chondrites of Kold-Bokkveld. In essence he repeated the work of Berzelius, Wohler and Clets, but on the much higher level of modern analytical chemistry. In meteorite bitumen there is a great deal more sulphur, chlorine and nitrogen than in similar terrestrial compounds. This peculiarity forced Muller to the conclusion that bitumen in meteorites has an abiogenic origin.

M. Calvin, mentioned above, and S. Vaughn approached this problem from different positions. The report made by them at the 1960 International Symposium on the Study of Cosmic Space was very significantly entitled "Extraterrestrial Life. Some Organic Components of Meteorites and Their Significance for Possible Biological Evolution Outside of Earth."

The American scientists evaporated volatile substances and then passed them through a mass spectrometer. In these experiments they determined the relative mass of unknown molecules and also investigated the infrared and ultraviolet spectra of extracts taken from the carbonaceous compounds of the meteorite. The results were amazing.

From the carbonaceous chondrite they succeeded in extracting a substance as similar as two drops of water to cytosine, one of the four basic carriers of the "code of life" in the DNA molecule. They also found in the meteorite a mixture of hydrocarbons similar to petroleum or paraffin.

In the following year, 1961, in the New York Academy of Sciences, there was a lively discussion of the work of three other American chemists, G. Nagy, D. Hennessy and U. Maintain. From carbonaceous chondrites they were able to /76 extract a series of paraffins very similar to what goes into the composition of apple skins and beeswax. In connection with this, discussions about the problem of the origin of petroleum also increased.

However regrettable but we still do not know, as we should, the genesis of the fuel which moves airplanes, ships and automobiles. Was petroleum formed as a result of the dissociation of former living organisms or is "black gold" the product of complex abiogenic synthesis? If the first hypothesis is true, bitumen in meteorites can be considered as traces of extraterrestrial life. But if petroleum has an inorganic origin, meteoritic bitumen does not have any direct relationship with life outside the Earth.

We have already discussed experiments modeling the formation of high molecular carbonaceous compounds under conditions of interplanetary space. It is even easier to imagine a similar abiogenic synthesis in the situation of an Earthlike planet. The main thesis of those who do not consider meteorites as bearing the remains of any extraterrestrial organisms is that organic substances in the meteorites were produced abiogenically. This is the position held by Anders, Briggs, and G. P. Vdovykin, a young investigator of carbonaceous chondrites in the Soviet Union. In the opinion of the latter, "a study of the spectra of various celestial bodies proves that carbon is one of the most widespread elements in them: it is observed in the elemental form (C_2C_3) and in the form of compounds (CH_2, CN, CO_2, etc.) in all types of celestial bodies. These components of atmospheres and even of stellar space could polymerize with the formation of complex organic molecules [7].

The most animated discussions now concern the enigmatic "organized elements" (Figure 18). These old inclusions were first noticed in 1961 by G. Nagy and D. Claus in their investigation of specimens of four carbonaceous chondrites. Outwardly they resembled terrestrial fossilized microscopic seaweeds. The Americans divided them into five types of objects according to morphological features, including evidences of pairing, as if deceased in the process of cellular division. Almost all of these "organized elements" resembled the most simple plants living only in water, and this obviously, in the /77
opinion of Nagy and Claus, eliminated any possiblity of the meteorite having been contaminated by the ground. Later, F. Staplin and others noted "organized elements" in a series of carbonaceous chondrites with all observers noticing their similarity to several one-celled seaweeds.

In 1962 the Leningrad geologist B. V. Timofeyev separated some old spore--shaped formations from the Saratov and Migei meteorites. There were more than a score of them, greenish grey, minute, hollow, almost spherical shells with diameters from 10 to 60 microns. The shells proved to have one layer and differed in thickness, sometimes crumbled into sharply outlined wrinkles. In the words of the scientist "the surface of the shells was smooth, rarely rugged. In one of the forms a round opening was visible, a stoma characteristic of some unicellular seaweeds. Many of the findings referred to can be compared with very ancient fossilized unicellular seaweed on the Earth, living more than 600 million years ago, but it is not possible to relate them to any group of the vegetable kingdom of our planet" [8].

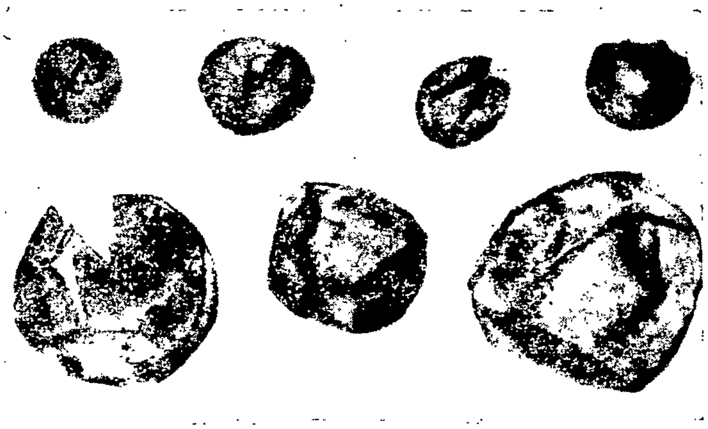

Figure 18. "Organized Elements" Taken From Various Meteorites.

Skeptics do not agree with these opinions. They have persisted and still persist in the belief that the so-called "organized elements" represent inorganic inclusions of the meteorite or, at best, terrestrial organisms caught onto the meteorite when it was "contaminated." /78

In 1963, Anders and his colleagues showed that some of the "organized elements" are very similar to the grains of ragweed pollen which have long been known as one of the contaminants of the New York air. On the other hand, at the Meteorite Conference in Moscow in 1964, Anders showed some photographs of suspicious pods found inside the Orgueil meteorite. It is noteworthy that the native country of this plant is Southern France on whose soil the meteorite was found.

However, these objections are not very persuasive. Detailed study of the "organized elements" has shown that even morphologically they are not quite identical to terrestrial fossilized seaweed, although they do resemble them in general characteristics. In order to refute the suspicion of meteorite contamination, some controlling tests were set up. In the museums and laboratories mentioned, where the meteorites are kept, specimens of the dust were taken. However, nothing was found in these tests resembling the "organized elements" of the meteorites. Nor were any found in the bituminous specimens of mountain rocks kept in the museums near the meteorities.

In 1963 Nagy and his coworkers investigated the suspicious inclusions by means of ultraviolet spectroscopy. The spectrum found was not at all that of inorganic inclusions.

The total amount of "organized elements" in meteorites is very great. According to the data of D. Claus (1964), in the small piece of the Orgueil meteorite, totalling about 1 milligram, 1,534 "organized elements" were found. Their size distribution, incidentally, is not at all characteristic of mineral grains. It was already shown three years before that in the Orgueil meteorite carbonaceous groups with an odd number of carbon atoms, characteristic only of materials of biogenic origin, predominate.

Some materials, synthesized by living organisms, possess so-called "optical activity". If a polarized ray of light is passed through such materials, i.e., a light beam in which the oscillations occur only in one definite plane, the optical activity of the substances changes this "plane of polarization". /79 It is noteworthy that optical activity is a characteristic property only of those organic materials which have come into being as a result of biogenic synthesis. This means that this property is a perfect indicator of life.

Attempts were made for a long time to detect optical activity in organic materials in meteorites but, alas, unsuccessfully. Only in 1964 did Nagy and his colleagues show that the organic material of the carbonaceous chondrite Orgueil is optically active. It turned the plane of polarization, but it turned it to the left, while in the control experiments with dust and other biological contaminants of the meteorite, taken from the same laboratory, the plane of polarization was turned to the right. Let us note that organic material, taken from a second meteorite, did not exhibit any optical activity at all.

Soviet scientists have participated actively in this entire discussion. In 1966 geologists from the Kirghiz SSR, under the leadership of A. S. Lopuhin, subjected specimens from the Saratov meteorite to controlled analysis [9]. In the testing process material was obtained which had previously been cleaned of any terrestrial vegetative elements which could have gotten to the meteorite. Nevertheless, in the meteorite were found large amounts of differently shaped spheroidal or compressed shells which could not be attributed to mineral formations in their outward appearance, their structure and their optical qualities.

The diameters of the shells, colored grey and sometimes with a brownish hue, varied from 10 to 100 microns. Particularly curious are small paired shells, tightened as if with a belt; do we actually have in front of us organisms which have died at the very moment of birth? As A. S. Lopukhin notes, "if we put ourselves in the position of researchers who mistake their findings of vegetative remains in meteoritic materials for terrestrial ones, it is natural to consider meteorites as fragments of a planet which at the moment of catastrophe was at a definite stage of development which predetermined the emergence on it of a comparatively high vegetative development."

The controversy about the organic material of meteorites has still not been settled today [10]. Although, judging from all appearances, meteorites do bear the remains of some forms of extraterrestrial life, this conclusion is not universally accepted. Newer and newer controlled tests are necessary with /80
due observance of stricter sterility, and new investigations of organic materials on meteorites, which should also cast light upon the origin of the asteroids, are needed.

In a collective article Academicians V. G. Fesenkov, A. A. Imshenetskiy and A. I. Oparin recently wrote[17] that the main task of these investigators "consists of definitively solving the problem of whether the organic material found on meteorites has a biogenic origin (i.e., does it present the result of animate processes) or was it formed by chemical reactions without any live participation."

THE ENIGMA OF TEKTITES

In some museum meteorites it is possible to find old vitreous formations. Outwardly these are pieces of dark green or sometimes black glass of very different shapes. Some of them remind one of small dumbbells or flanges, others resemble pears, onions, fingers and hollow spheres. Nonspecialists can sometimes confuse them with fragments of regular bottle glass.

At the beginning of the present century these old formations were called tektites (from the Greek word "tektos" which means "fused"). They differ in

[17]See p. 119 of reference [7].

size from tiny glassy beads to pieces comparable in size to a hen's egg and weighing almost a half kg.

Tektites attracted the attention of our distant ancestors. In the Danube region, at one of the settlements of the Stone Age people (25,000 years ago), tektites have been found which were evidently used by primeval people in their primitive agriculture.

Two hundred years ago, in the vicinity of the Vltava River in the territory of modern Czechoslovakia, local peasants "plowed up" wonderful glassy stones of unknown origin while working their fields. They polished them, and then the glassy pebbles became shiny, beautiful and of a smooth dark green surface. They began to make beads and other ornaments, successfully used by Bohemian girls, from tektites. Tektites found in Czechoslovakia were given the name "moidavites."

Later tektites were discovered in other places of the Earth. During his /81
trip around the world on the ship "Beagle" in 1884, Charles Darwin found tektites on the island of Tasmania ("tasmanites"). Considering the tektites to be terrestrial formations, Darwin described them as a variety of volcanic bomb hurled from volcanic craters at the time of eruption.

Later tektites ("australites") were discovered at various spots in Australia; these amazed the scientists by their unusual form (Figure 19). Some of them were reminiscent of buttons, others resembled mushrooms and a third group looked like hourglasses. There are also hollow vitreous balls the size of an apple with walls a fraction of a millimeter thick, as if some joker had blown something like a soap bubble out of crude glass!

The vitreous balls, as was established later, are not an exclusive property of Australia, but have been found among other tektites on many islands of the Malaysian Archipelago ("indochinites"). The Philippine Islands are rich in tektites ("philippinites"), and tektites have been found in West Africa and North America. It is curious to observe that tektites have still not been found in the immense territory of the Soviet Union nor at any point in South America. This is obviously caused by difficulty in searching; it is not easy to search for small pieces of dark glass, especially if upon accidentally finding such a fragment, a person does not know if his find is a fragment of a bottle or something exclusively valuable for study. It remains only to organize systematic and well planned searches for tektites and then there can be no doubt that they will be successful.

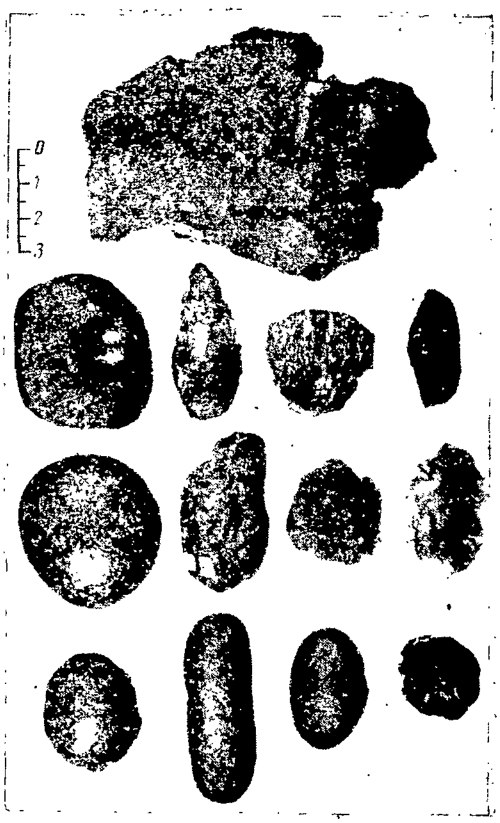

Figure 19. The External Appearance and Shape of Tektites.

No one has ever seen tektites fall, or at least science does not have any reliable reports of such available. However, in some countries tektites have been given names evidently referring to their extraterrestrial origin. Thus, for example, the local inhabitants of the Philippine Islands give tektites the names "excrement of the stars" and "solar stones," and the inhabitants of the Island of Hainan call tektites "moon stones".

Some tektites bear clear traces of flight in the terrestrial atmosphere. Imagine a typical Australite resembling a glassy button. As a number of observers have noted, this shape could be formed from an original vitreous sphere plunging into the terrestrial atmosphere at cosmic velocity. The front of the sphere fused, and the layer of /82
air encountered gradually compressed the original sphere and turned it into a button. The effect of the atmosphere on the flying tektite can successfully explain several other shapes of these enigmatic formations. Later, when the tektites were lying quietly upon the surface of the Earth, their form continued to change under the influence of purely geological factors (erosion, etc.) and

we are not always very successful in differentiating the activity of terrestrial and spacial factors, since the surface structure of tektites is sometimes extremely complex. /83

On the whole in all the meteorite collections of the world there are considered to be around 650,000 tektite specimens, material completely satisfactory for different kinds of investigation and generalization. The chemical and physical properties of tektites in many unique respects do not have any analogies on Earth nor in space.

From a physical-chemical point of view tektites are solid solutions of the oxides of different metals in salicic acid. Their chemical composition can be quite graphically illustrated with a special diagram, the so-called chemical spectrum. Their resemblance to acid volcanic rocks and so-called meteoritic impactites, vitreous formations caused by hitting the Earth and by the explosion of large meteorites, is obvious. But naturally there is an essential difference between them. Tektites contain very few volatile elements; the cause is evidently found in the high temperature heating to which these formations were subject. Tektites also contain such microelements as nickel, chromium and cobalt. Judging from the low germanium content in tektites, these objects cannot have an earthly origin.

The extreme dehydration of tektites demands attention. Terrestrial mountain rock contains an average of about 1% water. Regular bottle glass contains 0.02% water, while moldavites, outwardly resembling bottle glass, have not more than 0.0005%. On the average, tektites are 100 times more "dehydrated" than bottle glass. Even atomic impactites, those vitreous cinders formed during terrestrial atomic explosions, contain ten times more water than tektites. Again, we are almost forced to conclude that at some time tektites were subjected to exceptionally high heating. This same conclusion is also found by analyzing other physical properties of tektites.

Sometimes an impregnation of pure silicon dioxide is found in tektites, so-called lechatelierite. Inclusions of coesite, compact modification of silicon dioxide, are also found.

Perhaps the most curious fact is the finding in tektites of oxidized meteorite iron in which are found various types of meteoritic minerals, kamacite (nickel iron) and schreibersite. Recently, baddelyite (zirconium /84 dioxide), a mineral found only in synthetic glasses so far, has been found in tektites.

But a still more amazing finding made recently in one of the laboratories of the Kola branch of the Academy of Sciences of the USSR is that in some tektite specimens petroleum asphalt has been found, identical with that in carbonaceous chondrites.

Just what are tektites, and what is the origin of these old fragments of crude glass?

The main chemical peculiarity of tektites is their volume of silicon dioxide SiO_2, sometimes making up 70 to 90% of the total mass of a tektite. An analogy involuntarily suggests itself with terrestrial sedimentary rocks, and in connection with this the American geochemist G. Urey has written:

"The chemical composition of tektites is strikingly similar to the composition of the most acid sedimentary rocks...such a chemical composition does not occur during any chemical processes known in nature, with the possible exception of some very rare and special events."

Most of the formations in tektites known to us are similar to so-called silica glass, pure glass of a silicate composition. The first crude silica glass, in the form of small vitreous pebbles, was discovered accidentally in the Libyan Desert as early as 1816. Detailed investigation of the Libyan glass was made by the English minerologist L. Spencer in the 30's of our century. This glass is found in a region with an oval shape (largest diameter 130 km, narrowest 53 km). Two hundred kilometers from these deposits were found numerous pieces of the same glass along with vitreous spearheads, quartz axes and other stone instruments of the ancient inhabitants of this area.

In the Libyan Desert, where the mysterious glass was discovered, there is not even the slightest trace of any meteorite crater. Still, it is a reliable fact that around and inside some explosive meteorite craters are found meteorite impactites (from the English word "impact") already mentioned above. Essentially this terrestrial rock, first fused by explosion and then solidified, naturally became mixed with the meteorite material too. Therefore it is not surprising that the meteorite impactites from the craters of Wabar (Arabia) and Henbury (Australia) have proved to be saturated with meteorite material in the form of tiny droplets of nickel iron and also impregnations of lechatelierite.

It would seem that the key to the explanation of the nature of tektites /85 had been found. However, in some regions of regular deposits of silica glass, where gigantic meteorite craters should be found, there is nothing to give testimony to the fall of a large meteorite. In such regions not a single typical tektite has been found. Obviously, tektites cannot be considered the product of the melting of terrestrial sand.

When lightning strikes sand, fulgurites are produced, vitreous branched tubes marking the path of the storm's discharge. It is curious that fulgurites contain lechatelierite, just like tektites, and different kinds of silica glass. It appears that the mechanism of formation of all these objects has something in common. However, it is impossible to identify tektites as regular fulgurites.

Finally, there is one more class of objects reminiscent of tektites, so-called atomic impactites. During atomic explosions on the surface of the Earth or not far above the Earth, silicate rocks are melted and turned into pieces of vitreous atomic cinders. Coesite, a crystallite silicon dioxide with an extremely compact "wrapping" of atoms is found both in meteorites and in atomic impactites. Not very long ago coesite was also found in tektites.

A general conclusion: we do not know of any object, either on the Earth nor in space, which can be identified with tektites. In the complete association of properties, various kinds of silica glass, particularly meteoritic and atomic impact types, seem closest to tektites.

The famous Soviet investigator of tektites, G. G. Vorob'yev and his colleagues have carried out some interesting work. They collected almost all of the extremely extensive literature about tektites and arranged it on microfilms and coded on special punched cards. They assembled the most complete library on tektites in the world, containing several thousand books, articles and memoranda.

As G. G. Vorob'yev states, "work with punched cards" and "processing" of all of the literature according to a hundred thematic questions has shown that the overwhelming number of facts favors the cosmic origin of tektites. This was later confirmed by using electronic computers [11].

Thus, it is most likely that tektites are glassy meteorites. They are sometimes found in deposits of the ice age, in sand and in clay from the Tertiary /86 Age. The fact that tektites are plentiful in some regions and are not found at all in others is possibly an indication that these unusual celestial stones fell upon the Earth in a narrow belt. Is it possible to refer tektites and other meteorites to a common ancestral body or must a special source of formation, so far unknown, be sought for the vitreous meteorites? However, all these questions will be best settled in close connection with the general problem which is still unsolved, the origin of the asteroid ring.

WAS THERE EVER A PLANET PHAETON?

Ernst Chladnyy had clearly formulated two basic hypotheses capable of explaining the origin of the asteroids. In his book "The Origin of Various Masses of Native Iron, Notably That Found by Pallas," published in Riga in 1794, he wrote:

"If we begin from the point of view that these celestial bodies have somehow come into existence, this existence is unthinkable except as the uniting under the activity of the law of gravity of separate material particles loosely distributed in the space of the universe either as the result of the breakup of a large mass caused by an exterior shock or as the result of an internal explosion."

Olbers' hypothesis (in 1804) was the first hypothesis to explain the existence of the asteroids by the disintegration of a large planet. But parallel with this one other hypotheses were put forth which use a second possibility, the union of "particles of material scattered in universal space" into small planets. Laplace himself, stating that four of the asteroids known at his time were formed by gaseous rings of primeval mist assembling at some time into four aggregates, belonged to this point of view. It is curious that, from Laplace's point of view, the formation of four small planets instead of one large one was caused by the perturbing activity of Jupiter, which prevented the formation of an earth-like planet. This idea is also met in the modern hypothesis of O. Yu. Schmidt who also denies the reality of the planet Phaeton.

Although more than a few hypotheses about the origin of the asteroids have been proposed during the past and present centuries, almost all of them can be /87 reduced to one of the two main concepts mentioned above. However, hypotheses which do not recognize the asteroids as a separate individual class of celestial bodies, but consider the small planets, e.g., as a variety of comet, were also put forth.

William Herschel may be considered the originator of this third concept. In the opinion of the famous investigator of the stellar universe, "When comets are at a distance for a considerable length of time, their comas can shrink, if not completely, at least to a considerable extent, making them similar to stars. Then, they become asteroids." It is not hard to see that this hypothesis of Herschel did not explain much, but nevertheless it had its followers who tried to find not only qualitative but also quantitative confirmation of the expressed assumption. Of them, N. F. Bobrovnikov and S. K. Vsekhsvyatskiy deserve special mention.

The first of them expressed the hypothesis in 1931 that all asteroids have come from one large planet, captured at some time by Jupiter and then disintegrating into a large number of fragments. From the point of view of current data about comets, Bobrovnikov's hypothesis cannot stand up to criticism. The masses of cometary nuclei are too small to produce the rather massive asteroid ring, and in composition the structure of the cometary nuclei has nothing in common with the physical properties of the small planets. Nor can Bobrovnikov's hypothesis explain the reasons for the disintegration of the hypothetical gigantic comet and the nature of the existing asteroidal orbits. However, as Bobrovnikov himself noted, "in the present state of our knowledge of both comets and asteroids, it may be premature to construct a theory about their origin."

The basic idea, defended for many years by S. K. Vsekhsvyatskiy can be summed up by saying that the comets turn into asteroids after losing their gaseous shells. The comets themselves are the result of powerful eruptions ns (i.e., explosions) of processes on the planets and on some of their satellites, thus being essentially the products of powerful volcanic explosions. Expressed in present-day language, these ideas would be formulated as:

"A study of the physical nature and chemical composition of meteorites leaves no doubt of the fact that they must represent fragments from the crust of celestial bodies....

"The concept generally accepted today is that meteorites are bodies of an asteroid nature and that asteroids can be regarded as large meteoritic bodies. /88

"A study of the physical nature and brightness of asteroids leads to the conclusion that they have a fragmentary form, and their relationship to comets, expressed in peculiarity of movement and similar physical nature, make it possible to conclude that comets, after exhausting their supply of ice, must turn into asteroids or meteoritic bodies. In reality current short-period comets differ from asteroids only in possessing ice and smaller masses" [12].

There is no doubt of the fact that almost everywhere in the solar system can be seen explosive processes attaining exceptional power on the Sun and on the large planets. It is entirely possible that in the past the extent of these processes was much more imposing and that they played far from a secondary role in the life of the solar system. It cannot be denied that to a considerable degree some comets may be considered independent "volcanic bombs," hurled from the surface of planets and their satellites. But all this is not grounds for identifying comets with asteroids.

We have already noted the existence of different orbits for these celestial bodies and spoken against a communality of nature and origin. Not on a single comet has there ever been observed a nucleus similar, let us say, to Ceres nor to hundreds of other asteroids with diameters in the tens and hundreds of kms. The nuclei of comets consist basically of ices, while the asteroids suggest gigantic stones or iron meteorites. Can we, by ignoring these facts, consider the asteroids known to us to be cometary nuclei?

The cometary orbits are exceedingly varied, from small ellipses fitting within the orbit of Mars to the gigantic elliptical orbits of the long-period comets. S. K. Vsekhsvyatskiy's hypothesis does not at all explain how all of these orbits change into almost circular orbits, lying in general between the orbits of Mars and Jupiter, after the comet has lost its gases, and why this mysterious transformation takes place only after the "depletion" of the comet and has no direct relationship to the nature of its movement around the Sun nor to its orbital elements. Let us note in passing that some known comets (e.g., 1901-I) have completely lost their gases and nevertheless have a typical cometary /89
orbit. In short, there is no basis whatsoever for considering comets the ancestors of asteroids.

When O. Yu. Schmidt's hypothesis gained popularity during the 50's of the present century, experiments were carried out within the framework of this hypothesis to clarify the origin of the asteroid ring.

The Titius-Bode Law leaves room for the hypothetical Phaeton. The law of planetary distances, accepted by O. Yu. Schmidt, has various parameters for planets of the earthly type and for large planets. In essence there is no place left for a planet Phaeton, although O. Yu. Schmidt notes that, if sometime in the region of the contemporary asteroid belt "a planet were observed, it would be small, similar to the Earth and to Mars, but not to Jupiter" [13].

But in the opinion of O. Yu. Schmidt, no planet can be formed there, mainly because the perturbing influence of Jupiter would prevent it.

"Even in the early evolutionary stages of the preplanetary swarm," writes O. Yu. Schmidt, "the perturbations of growing Jupiter exercised an essential influence on the action of the bodies coming into existence in the asteroid belt by enlarging their mean eccentricities and the inclinations of their orbit and, at the same time, preventing their union.

"The limiting position of the asteroid belt, leading to a change in temperature of the particles, and the process of uniting into larger bodies being accompanied by substantial changes in chemical composition made it possible for the perturbations of Jupiter to exercise their influence. The vaporization of volatile substances forming the bodies led to their decay or, by lowering their toughness, facilitated their fragmentation by collision. In the same way the vaporization retarded the processes of forming large bodies in the asteroid belt and provided time for their orbits to be changed by perturbations from Jupiter."

In the opinion of O. Yu. Schmidt and his followers, in this way the evolution of the proto-planetary cloud in the asteroid belt region stopped at an intermediate stage. B. Yu. Levin writes, "a large number of bodies the size of a large asteroid were formed from the ring of dust. Indeed, our contemporary planets were formed from these bodies" [14]. It is easy to see that all these /90
discussions about the origin of the asteroids have a qualitative nature and that they have never been given a quantitative foundation. Still, the hypothesis of O. Yu. Schmidt remains only one of many cosmogonic hypotheses so far. Naturally there are no grounds at all for considering it a strictly reasoned theory explaining the origin of the planets clearly and indisputably. In addition, even if they agree with O. Yu. Schmidt's explanations, a great many facts remain unclear.

If the large asteroids, the "planetoids," are the building blocks from which the solar system was created, then why do scores and hundreds of asteroids have almost round and coplanar orbits, when the bodies of the asteroid masses, according to O. Yu. Schmidt's hypothesis, should have very elongated orbits /91
lying on different planes? On the other hand, with the "accumulation" of a large number of small particles of proto-planetary cloud into "planetoids" (and thus the asteroids), the latter ought to be almost spherical, while in fact all of the asteroids have a complex, irregular, fragmentary shape. Finally, the structure, position and other properties of meteorites, as will be shown below, provide evidence of the fact that a large earthlike planet was evidently the ancestor of the asteroids and meteorites. In other words, the old hypothesis of Olbers still seems today to be the most probable in comparison with all others.

In order to substantiate this position, let us look at the facts. Only they can serve as the cornerstone for any hypothesis, only indisputable facts can repudiate or, vice versa, confirm a suggested explanation. Are there facts which prove that at some time a large earthlike planet Phaeton revolved around the Sun between the orbits of Mars and Jupiter?

Let us once more recall that the mean value of the semi-major axis of the orbits of all known asteroids is equal to 2.8 AU, i.e., it completely fits the Titius-Bode Law. Although this law itself has not yet found any theoretical foundation and has an approximative character, it is still obvious that it reflects some objective regularity and that in this regularity the planet Phaeton is an indispensable member of the sequence.

If Phaeton really existed sometime, and then for some reason disintegrated into pieces under the influence of external forces, the mean trajectory of the fragments should evidently coincide with the trajectory in which the center of gravity of the parent body traveled, which is, however, far from obvious.

In the 50's of the present century G. F. Sultanov tried to find out if it were possible to correlate the distribution of orbits of current asteroids with the argument from the disintegration of an original planet. On the basis of computations he posited several simplified assumptions, namely that the original planet suffered disintegration at the aphelion or perihelion of its orbit, and also that the velocity of the fragments is uniform and uniformly distributed in all directions, so collisions between them did not occur. Under these conditions, hardly corresponding to reality, G. F. Sultanov came to the conclusion /92 that it is impossible to explain the existence of the current asteroid belt by the disintegration of one planet. But this conclusion, as Academician V. G. Fesenkov [15][18] correctly notes in turn, could have been expected earlier since the fragments of the ancestral planet are known to have collided with one another and this considerably complicated the original picture, which can hardly be solved in general with the methods of celestial mechanics, whether Olbers hypothesis is correct or not. A solution to the problem requires further examination of the physical properties of asteroids.

[18]See p. 125 of [15].

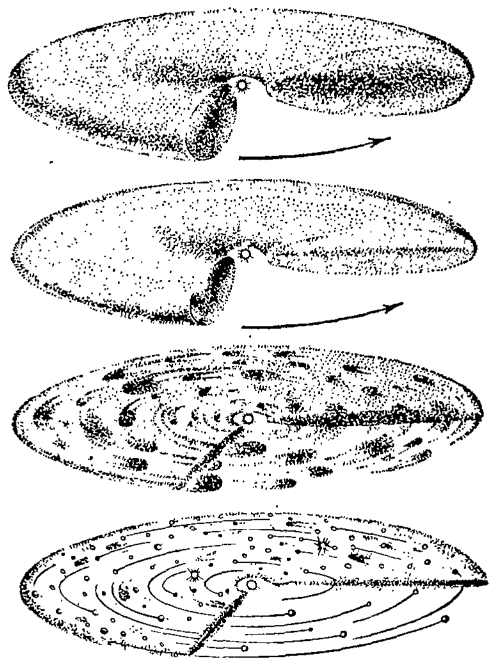

Figure 20. Formation of Proto-Planetary Asteroidal Bodies According to O. Yu. Schmidt's Hypothesis.

The irregular and fragmentary shape of all known asteroids and meteorites graphically illustrates the gradual and continual destruction and fragmentation of bodies in the asteroid belt. Even the largest of the asteroids are fragments of still larger bodies and not at all the product of previous condensation of material from the preplanetary cloud.

Sometimes the suggestion is expressed that several (50) comparatively small ancestoral bodies were the ancestors of the contemporary asteroid belt. However, as J. Kuiper has shown, even if these initial bodies lay in almost the same plane and had almost circular orbits, collisions between them could have been quite rare, one collision after 30 billion years, i.e., after a period which exceeds the age of the planetary system! This almost insurmountable difficulty must be regarded as one more argument in favor of the reality of Phaeton.

Under some conditions the Widmanstaetten figures can be obtained artificially as a product of a metallurgical process. But under such conditions they are obtained as almost microscopic particles. The large scale of the Widmanstaetten figures in iron meteorites can obviously be explained by the fact that these meteorites were formed under extremely high pressure, i.e., in the depths of a large planet. However, the question of the source of the Widmanstaetten figures in meteorites has not yet been definitively answered.

More than one attempt has been made to create a hypothetical model of Phaeton. The outstanding Soviet geologist, Academician A. N. Zavaritskiy, has done this most successfully. Presuming that the number of occurrences of meteorites of various classes is proportional to the volume of corresponding (according to composition) parts of Phaeton, Zavaritskiy made a graphic representation of the structure of this once possibly existing planet (Figure 21). /93

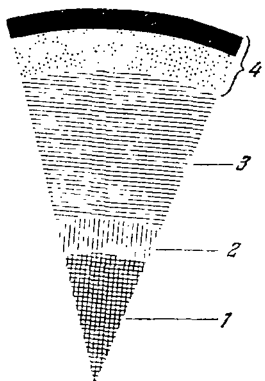

Figure 21. The Structure of the Hypothetical Planet Phaeton According to A. N. Zavaritskiy. 1, Iron-nickel nucleus; 2, Iron--silicate zone; 3, Periodotitic zone; 4, Basalt crust and blister layer.

The radius of its iron core amounted approximately to 0.4 of the radius of the entire planet. The exterior solid crust of Phaeton, corresponding to the basalt layer of the Earth, was approximately 1.5% of the radius of the planet in thickness (on the Earth it is about 1%). The total mass of Phaeton according to Zavaritskiy, as already discussed, was not less than 0.1 of the mass of the Earth. As a matter of fact, it could have been considerably greater, since after the catastrophe a considerable amount of substance (generally in the form of dust and micrometeorite grains) left the asteroid zone forever.

Finally, while this theoretical "reconstruction" by itself cannot prove the reality of Phaeton, at any rate it does not contradict Olbers' hypothesis.

Diamonds and cohenite are found in meteorites. According to some theoretical computations both of these materials could only have gotten their observable structure under a pressure of not less than 30,000 atm, i.e., inside a body with no less mass than the moon (which, by the way, is 100 times greater than the mass of Ceres.) According to some experimental data, temperatures on the order of 1,200°C and pressures greater than 55,000 atm, already corresponding to the depths of an earthlike planet, are indispensible for the formation of diamonds of the meteoritic type. But since the problem of diamond formation is very complex [16] and has not yet been solved, the presence of diamonds in meteorites may be explained differently.

The residual magnetism in meteorites may have been caused through the magnetic pole of the parent planet. According to the data of Ye. G. Gus'kova, who inspected 270 specimens of meteorites of all three types in 1963, the magnetizing field had an intensity on the order of 0.2 oersteds for rock /94 meteorites and 0.6 oersteds for iron ones, i.e., in this ratio they were similar to the geomagnetic pole. Analyzing all possible sources of the magnetization, Ye. G. Gus'kova reached the conclusion that "the magnetism of meteorites was induced in the parent bodies which had natural magnetic poles, since it is difficult to expect anywhere in cosmic space a simultaneous occurrence of high temperatures and constant magnetic fields, necessary for the formation of thermoremanent magnetism" [17].

I. Kern also reached an analogous conclusion by showing that chondrites cooled in the magnetic field of the parent planet and that the intensity of this field was close to the magnetic field intensity of the Earth.

Space investigations of the past decade have shown that magnetic fields are evidently indigenous only for large celestial bodies. They are practically lacking for the Moon, Venus and Mars. On the other hand, there are serious reasons for assuming that Jupiter is surrounded by powerful radiation belts and thus has a very intense magnetic field. If these conclusions are supported in the future, the residual magnetism of meteorites can become a convincing argument in favor of the reality of Phaeton.

However ponderable the above arguments may be, the main thing which is impelling some investigators today to return to Obers' hypothesis again lies in something else. The organic material of meteorites, complex high molecular carbonaceous compounds found in them, and particularly enigmatic "organized elements," surprisingly similar to primitive forms of life, are perhaps the main argument of contemporary supporters of Olbers' hypothesis. When it is possible to imagine (and even to model in the laboratory) the abiogenic synthesis of some protein substances, when it is possible to grant that synthesis of such a type has taken place and may be taking place today in interplanetary space; there is scarcely any risk involved in maintaining that life originated there also. Let us recall that it is the opinion of investigators that remains of living organisms were discovered on certain meteorites.

Such a pattern seems unreal. It is possible to argue about some particular features of the hypothesis of A. I. Oparin and of other hypotheses similar to his, but it is hardly possible to doubt the fact that an earthlike environment is indispensible for the rise of protein forms of life. A planet on which such an event took place must resemble Earth. The necessary conclusion from this is that Phaeton resembled Earth. /95

However, it would be erroneous to consider the discussions referred to as indisputable proof of the existence of Phaeton. The problem is too complex to be described to nonspecialists. Let us simply refer to several difficulties which even today make it necessary to consider Olbers' hypothesis as merely hypothetical.

The Soviet meteorite investigator A. A. Yavnel' distinguished at least five groups of meteorites which are very different from one another in chemical properties. Sometimes these differences can really be of various types. Let us say that the Sikhote-Alin meteorite is made up of 6% nickel, while the well--known Oktibago-Kounti meteorite has a ten times greater percentage of nickel. This shows that it is not an iron meteorite with the addition of nickel, but a nickel meteorite with the addition of iron.

Yavnel' believes that every group of meteorites identified by him was formed independently in a separate celestial body.

However, let us note that this conclusion cannot be considered indisputable. If the parent body were a large planet, conditions could have been extremely varied in different parts of it, whence the substantial deviation in chemical properties of meteorites. On the other hand (let us remind the reader of Kriper's work), five or even ten ancestral bodies could not be transformed into that finely divided asteroid belt which we observe at the present time.

Much more serious are the arguments of the opponents of Olbers' hypothesis which are based on the great spread of the so-called cosmic ages of meteorites.

Traveling through interplanetary space, a meteorite is continuously subjected to the effect of cosmic rays, fluxes of rapid, energetic particles basically protons and nuclei of helium atoms. On the surface layers of meteorites these particles cause various nuclear reactions, as a result of which new, so-called cosmogonic elements are produced, products of the irradiation of meteorites by cosmic rays. If we postulate that the intensity of cosmic rays has always /96 been what it is now, it is possible to compute by the percentage of cosmic elements the cosmic age of a meteorite, i.e., the length of time it has been in interplanetary space as an individual celestial body.

A different picture is found inside a fairly large ancestral body. Even at a depth on the order of a few decimeters, the rocks are practically shielded from the activity of cosmic rays (in the sense that nuclear reactions with the formation of cosmogonic elements do not occur there). In this case it is naturally possible for radioactive decay to take place, e.g., such as occurs in terrestrial uranium ores. According to the percentage of decay products from uranium, it is possible to estimate the age of the rock. But this will not be its cosmic age, but rather the period which has passed since the time the given celestial body was formed (analogous to the age of the Earth).

Although the theoretical side of the question may seem quite simple, the practical determination of age of a meteorite entails numerous difficulties. This work is very meticulous and tedious, and we recommend to the reader interested in details the literature where this question is discussed quite fully [18].

In regard to the period which has passed since the time the meteoritic substance was formed, a mean age close to 4 1/2 billion years is found for different meteorites by different methods. This is the same age found for the Earth by analogous methods, and thus it is accepted as the age of the planetary system.

The cosmic age of meteorites is a different matter. Here the disparity of results is very great. While the cosmic age of stone meteorites is 20 to 25 million years on the average, for iron meteorites it is longer, on the average 240 to 290 million years. It appears that the formation of meteorites of different classes occurred at different times; in other words, it is not possible to explain the origin of meteorites and asteroids by the single explosion of a large ancestral body.

There is no denying that all of these chronological difficulties may be associated with imperfections in contemporary methods of determining the age of meteorites and with errors in some of the postulates accepted today. /97

For example, is the intensity of cosmic radiation constant? According to the data from the interplanetary robot station "Mars 1", the intensity of cosmic rays of solar origin fluctuated by 80% in the short period of just a few years. On the other hand, the hypothesis which considers the flash of a supernova star in the galactic vicinity of the Sun to be the cause of the rapid extinction of dwarf stars seems to be quite probable. At the time of such a flash the intensity of the galactic cosmic rays may increase a million times, and it is natural that this would sharply increase the amount of cosmogonic elements in meteorites (which we would consider a sign of the great age of meteorites). In short, the postulate about the constancy of cosmic radiation is at least doubtful.

Now imagine a second situation. Upon the explosion of a large ancestral planet at some time, a small asteroid came into being with a diameter, let us say, of several meters. Its entire surface layer then began to experience cosmic radiation, the age "counter" began to work. Several million years passed, and our asteroid collided with another one and broke into fragments with diameters less than a meter. Now, cosmogonic elements formed both on those fragments which were earlier at the surface of the asteroid and on those which were inside. What will happen when the two kinds of meteorites enter our laboratories? Judging from their cosmogonic element content, we will classify them by different cosmic age. We shall be prone to consider one of the fragments as having formed several million years after others, although in fact they separated from the original large planet at the same time.

We have already stressed that the structure of meteorites provides testimony about the complexity of the life they have led. Disintegration and fragmentation were replaced by consolidation and slow cooling was replaced by high temperature heating. We do not know the details of all this prehistory, and we do not have any certitude that all of these metamorphoses did not affect the amount of cosmogonic elements. But then what value does our currently held chronology have?

In some modern works an attempt has been made to associate the velocity of radioactive decay with the changing (according to Dirac) force of gravitational interaction. If there is a grain of fact in these investigations, /98 they will cause our entire currently accepted methodology of determining meteorite age to be rejected [19].

The conclusion is clear: the chronology accepted everywhere in contemporary meteorite studies cannot be considered absolutely indisputable, and therefore disparity in the ages of different meteorites cannot serve as a decisive argument against Olbers' hypothesis.

Let us assume that Olbers' hypothesis is true. What was it that forced Phaeton to break into pieces, what causes led this planet to its catastrophic destruction?

There have been many attempts to answer this question, but the problem still seems unsolved. In 1950, V. G. Fesenkov suggested that Phaeton once came too close to Jupiter and that the effect of the latter's powerful attraction caused sharp changes in the pressure and specific heat of Phaeton, with a rise in temperature and the formation of superheated gas, and Phaeton exploded "like a bomb".

This suggestion has never had a sufficient physical basis. The distribution of the asteroid orbits proves that the ancestral planet never came close to Jupiter. Later even the author of this hypothesis preferred to abandon his hypothesis.

In 1949 I. I. Putilin developed his hypothesis of the disintegration of Phaeton because of its very rapid specific rotation. However, this "rotational hypothesis" found no supporters because of its poor foundations. In particular

I. I. Putilin did not at all explain the causes of so rapid a rotation of Phaeton (linear velocity at its equator on the order of 3 km per second!).

The "volcanic" hypothesis, which considers the cause of Phaeton's disintegration to be powerful volcanic or other explosive processes occurring on it, seems to be much more likely. In different varieties and forms this hypothesis has been defended by many scientists, particularly by A. N. Zavaritskiy [20]. S. K. Vsekhsvyatskiy has persuasively pointed out the possibility of past development of powerful eruptive processes on bodies of the solar system. It cannot be ruled out that such types of processes also led to /99
the destruction and disintegration of one of the major planets of the solar system. However, let us point out that this hypothesis, defended at present by A. Ringwood and others, does not yet have a satisfactorily clear basis.

If tektites are vitreous meteorites, can their origin not be related to the existence of the asteroid ring? Finally, would it be a mistake to consider all meteoric bodies without exception to be fragments of the hypothetical Phaeton? It is completely conceivable (speaking theoretically) that there are other sources for the origins of meteoric bodies. They could be, let us say, "volcanic bombs," hurled from the surface of the large planets or fragments of small planetary satellites knocked into interplanetary space by a collision between the satellite and a meteorite.

Some researchers, such as D. O'Keefe, consider tektites to be fragments of lunar rocks hurled into space by the impact of falling meteorites. This latter point of view scarcely corresponds to reality, not only because the composition of the surface lunar rocks (judged by the latest cosmic experiments) is not at all similar to the composition of tektites, but also because the probability of fragments falling from the moon to the Earth is very slight.

The cosmogonic age of tektites is very short (on the order of a million years), and this obviously prevents their being united with the other meteorites. But if, conscious of the imperfection of contemporary meteoritic chronology, we ignore this fact, it is possible to assume that tektites were formed from superficial silicate layers of Phaeton. Unfortunately we also meet annoying discrepancies here, too. Tektite formation took place at very high temperatures, while the carbonaceous chondrites (which, judging from appearances, must also have been formed from the surface layers of Phaeton) were evidently never subjected to any great heat (or they would not have contained "organic material").

It is still not clear how we can escape these contradictions.

In the summer of 1965 at the 20th International Congress on Theoretical and Applied Chemistry, Academician A. P. Vinogradov reported that at the present time chondrites can be produced experimentally.

They are formed from plasma during underground nuclear explosions, and the more powerful the explosion, the smaller the size of the globules. Recall the similarity between tektites and nuclear impactites. Do not these facts attest to some kind of nuclear processes accompanying the disintegration of Phaeton? /100
Difficulties relating to the basis of Olbers' hypothesis compel some modern researchers to look for completely new ways of solving this problem. An interesting hypothesis was recently published by Academician V. G. Fesenkov [21].

Analyzing the quantitative ratios of various radioactive isotopes which are found in meteoritic compositions, V. G. Fesenkov comes to the conclusion that "the Earth and the other planets were formed at the same time from the Sun and that thus the process of forming our planetary system must be organically related to the general galactic process of star formation." The Soviet scientist assigns a decisive role in this process to the flashes of so-called supernova stars during which the exploding star not only radiates into space enormous quantities of matter and energy, but also carries out a no less important process, the synthesis of heavy elements.

In the interstellar nebulous medium V. G. Fesenkov long ago discovered old filaments and condensations evidently related to some stars located in the sky network. It is possible that all of these observations illustrate for us the process of the birth of stars in the interstellar medium. But then, some substances and even separate structural details (chondries), found now in meteorites, could have been formed in the very same medium.

"The processes in the oldest stage of the development of the solar system were notable for their extreme complexity," writes V. G. Fesenkov. "In the beginning this was some kind of process of forming heavy, including short-lived, elements, evidently the flashes of a supernova accompanied by the emission of shock waves with a compression of the material in the nebulous mistiness in which numerous concentrations rapidly appeared around a central body, the Sun in formation.

"During reciprical collisions in these proto-planetary concentrations, local small and short-term periods of heating occurred, which led to the formation of chondrites and also to a large number of fairly complex organic compounds.

"In the evolving asteroid bodies may have occurred gradual crystallization of iron-nickel siderites; other similar bodies evidently experienced, even in /101 the early stages of their existence, numerous collisions and destruction."

If everything actually happened as V. G. Fesenkov suggests, then the hypothetical earthlike planet Phaeton simply never existed.

To sum up, it must be recognized that at present, 170 years after the discovery of the first asteroid, the problem of the origin of the asteroid belt is still unsolved.

Many hypotheses have been advanced, but so far not a single one of them can be considered well founded and conclusive. In such a situation a natural conclusion is to continue with research and to accumulate more and more new facts.

Although meteoritic studies and classical "observational" astronomy are far from having fulfilled all their possibilities in this field of knowledge, the successfully developing field of astronautics is exposing completely new and occasionally almost fantastic perspectives to asteroid investigators. It may be that only direct space experiments will decisively reveal the secret of the origin of the small planets.

ASTEROIDS AND ASTRONAUTICS

In our days the study of the small planets must and should be connected with some problems of astronautics. This refers primarily to the solution of several astronautical tasks.

By studying the orbits of the small planets it is possible to determine the perturbations caused by Jupiter and other planets in their motions, and it is possible to determine the masses of the planets according to the amount of perturbation. It is scarcely necessary to explain that in flight to planets the trajectories computed depend not only upon the distance to the planets but also upon their mass. In this connection classical celestial mechanical methods are still unique and have no "competitors."

As is known, some of the stars (e.g., Canopus) have been used as points of orientation for stabilizing systems on spacecrafts. In the future, especially on interplanetary flights, the use of stars for orientation will be even more widespread. In this connection, it is obviously necessary to know as exactly as possible the relative positions of the stars in the sky and their celestial equatorial coordinates. Maximum precision in stellar catalogs is /102
urgently needed for astronauts.

In the last analysis the problem leads to as exact as possible a determination of the position of points of the universal equinox--the beginning of computations in the equatorial system of coordinates. This problem can be solved by observing the planets for which an exact theory of motion has been worked out. The most convenient of the planets are the asteroids, as their starlike appearance facilitates measurement and eliminates a number of systematic errors. Thus, one more connection between the small planets and astronautics is envisaged.

Included in the work of the near future in conquering space, the asteroid belt appears as a region of increased meteoritic danger, i.e., as an obstacle to flight towards the distant planets, Jupiter, Saturn, Uranus, Neptune and Pluto. But possibly there exists another positive relationship with the asteroids.

The small mass and scanty dimensions of these bodies facilitate landing on the largest of them (let us say Ceres) or "mating" with the others, as even for Ceres the critical velocity amounts to only 300 m/sec. Let us note that at the present time the elements of the asteroid orbits are known within large limits of error which still make "a hit" with them, i.e., sending spacecraft from Earth to the vicinity of the asteroids, difficult (not to speak of landing on their surface). Taking off from asteroids is also presented in principle as a fairly easy undertaking. In short, the lack of an atmosphere and a significant field of attraction facilitate direct study of the small planets. But what can such investigations give to science? Can the small planets be used for the benefit of mankind?

It is possible that some of the asteroids are rich in precious natural minerals. Then their wealth in ores can be mined or treated on the spot, or transported to Earth. Either is possible in theory, although accompanied by gigantic technical difficulties.

But the main point is probably not included in these very utilitarian goals. Much more important is the information about the past of the solar system, the origin of the asteroid belt and the nature of the asteroids, knowledge which we will obtain by stepping onto their surfaces.

Even now, at the beginning of the direct study of the asteroids by astronautic methods, there is reason to think that very unexpected surprises await us.

Do you recall that the study of meteorites began with a struggle against /103
inertia and fallacy? Two hundred years ago official science did not recognize the reality of meteorites. After 1803, when the Paris Academy of Sciences appeared forced to recognize that "stones can fall from the sky," the interesting process of the gradual expansion of meteorite classification began.

When Berzelius in 1834 found the first carbonaceous chondrite in his hands, the scientist thought for a long time that there had been some kind of mistake: even at that time only iron and stone meteorites were officially recognized.

Although Chladnyy had already adduced incontrovertible proof of the fact that the famous Pallas iron was a meteorite, people refused to believe him for a long time. Only in 1902 when a meteor similar in nature to the Pallas chunk fell and was found, was the classification of meteorites officially enlarged by pallasites, a curious variety of stone meteorites. It is conceivable that direct study of the asteroids will considerably broaden the contemporary classification of meteorites.

Among the wild American plans for unleashing thermonuclear war in space there has also appeared a suggestion for using the small planets as asteroid bombs! A concrete "project" of this type was suggested by K. Koul, a worker of the General Electric Company and the author of monographs about asteroids. He would send a spaceship with a team of astronauts on board into the asteroid belt. They would "moor" on an asteroid of, let us say, a diameter of 52 km and a mass of 500 million tons and then, by making use of the engines of the craft, they would direct this asteroid to a designated area of the terrestrial globe. The explosion of such an asteroid as it hit the Earth may be considered as equal to the simultaneous explosion of a billion hydrogen bombs of a moderate size. In 1966 the Koul project was discussed in the Pentagon[19] [22]. Naturally, "projects" of this type need no commentary.

Our plans are different. We are not mastering space for grasping, aggressive, antihumanitarian purposes, but for the sake of new resources in space, matter, energy and for a transformation of mankind into a cosmic civilization.

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[19] See [22], p. 95.

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